Quality Properties of Orange Fruit Leather as Affected by Structuring Agents

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Abstact: The aim of the current study was to investigate the effects of different structuring agents (corn starch, wheat starch, and rice flour) on the physicochemical, color, mineral, mechanical, and sensory properties of orange fruit leather. Significant differences were observed among formulations depending on the type of structural ingredient. The thickness ranged from 1.74 mm to 2.07 mm, and the moisture content fluctuated between 18.72% and 20.17%. Water activity levels significantly decreased in samples made with rice flour (0.55), suggesting enhanced water retention. The protein content notably increased in rice flour-enriched samples (2.50%), while pH levels remained consistent (3.29–3.34). Colour analysis showed minimal changes in L*, a*, and b* values, indicating that pigment stability was preserved across the different formulations. The results for mineral composition indicated that rice flour considerably boosted both macro- and micro-mineral levels, especially calcium, iron, potassium, magnesium, manganese, phosphorus, and zinc. Texture profile analysis indicated that the addition of rice flour significantly diminished hardness, fracturability, gumminess, and chewiness, reflecting a less robust structural network. Tensile analysis demonstrated lower peak load and work of deformation in samples containing rice flour, while the deformation values did not vary. Sensory assessment revealed that wheat starch and corn starch samples received higher ratings for taste, texture, and overall acceptability, while rice flour samples were less favoured because of their softer texture and diminished structural integrity. These results emphasize the significance of starch selection in influencing the final quality of fruit leather products and offer useful insights for the formulation of functional foods.

Keywords: Orange fruit leather, starch substitution, structuring agent, rice flour

Yapılandırıcı Ajanların Portakal Pestilinin Kalite Özellikleri Üzerindeki Etkisi

Öz: *Bu çalışmanın amacı, farklı yapılandırıcı maddelerin (mısır nişastası, buğday nişastası ve pirinç unu) portakal meyve kurusunun fizikokimyasal, renk, mineral, mekanik ve duyusal özellikleri üzerindeki etkilerini araştırmaktır. Yapılandırıcı bileşenin türüne bağlı olarak formülasyonlar arasında önemli farklılıklar gözlemlenmiştir. Kalınlık 1,74 mm ile 2,07 mm arasında değişmiş ve nem içeriği %18,72 ile %20,17 arasında dalgalanmıştır. Pirinç unu ile yapılan örneklerde su aktivitesi seviyeleri önemli ölçüde azalmıştır (0,55), bu da su tutma kapasitesinin arttığını göstermektedir. Protein içeriği pirinç unuyla zenginleştirilmiş örneklerde belirgin şekilde artmıştır (%2,50), pH seviyeleri ise sabit kalmıştır (3,29–3,34). Renk analizi, L*, a* ve b* değerlerinde minimal değişiklikler göstermiş, bu da pigment stabilitesinin farklı formülasyonlarda korunduğunu göstermektedir. Mineral bileşimi sonuçları, pirinç ununun hem makro hem de mikro mineral seviyelerini, özellikle kalsiyum, demir, potasyum, magnezyum, manganez, fosfor ve çinko seviyelerini önemli ölçüde artırdığını göstermiştir. Doku profili analizi, pirinç unu ilavesinin sertliği, kırılganlığı, yapışkanlığı ve çiğnenebilirliği önemli ölçüde azalttığını ve daha az sağlam bir yapısal ağı yansıttığını gösterdi. Çekme analizi, pirinç unu içeren numunelerde daha düşük tepe yükü ve deformasyon işi gösterirken, deformasyon değerlerinde bir değişiklik gözlenmedi. Duyusal değerlendirme, buğday nişastası ve mısır nişastası numunelerinin tat, doku ve genel kabul edilebilirlik açısından daha yüksek puanlar aldığını, pirinç unu numunelerinin ise daha yumuşak dokuları ve azalmış yapısal bütünlükleri nedeniyle daha az beğenildiğini ortaya koydu. Bu sonuçlar, meyve kurusu ürünlerinin nihai kalitesini etkilemede nişasta seçiminin önemini vurgulamakta ve fonksiyonel gıdaların formülasyonu için faydalı bilgiler sunmaktadır.*

Anahtar Kelimeler: *Portakal pestili, nişasta ikamesi, yapılandırıcı madde, pirinç unu*

INTRODUCTION

Fruit leather, also referred to as a fruit bar or fruit slab, is a dehydrated fruit-based confectionery product commonly consumed as a snack or dessert, characterized by its chewy texture, natural low-fat content, high fibre and carbohydrate composition, and convenient storage and packaging properties (Diamante et al., 2014). Fruit leather is highly valued for its rich flavour, long shelf life, and convenience, and is becoming more recognized as a functional snack alternative for both adults and children. Fruit leather production is an effective approach for valorising imperfect or seasonal fruits, helping to reduce postharvest losses and minimize food waste (Abdullah et al., 2025).

Drying is the essential process in producing fruit leather, and it has a major impact on the physicochemical, structural, and sensory characteristics of the end product. Moisture content and water activity are especially important factors that affect microbial safety, texture, and the stability of storage. Fruit leathers derived from various fruits are generally dehydrated to moisture contents below about 25% and water activity

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values lower than 0.70 (Menezes Rodrigues et al., 2023), which contributes to microbiological stability and the development of a characteristic chewy texture. However, over-drying may result in a brittle texture, whereas inadequate drying can cause stickiness and diminish shelf life stability. Fruit leathers offer an innovative and sustainable alternative for fruit preservation, extending shelf life and reducing food waste, which has led to increasing interest in recent years in optimizing their formulations (Silva and Miano, 2026).

Starches from various plant sources like corn, wheat, potato and rice are frequently utilized to enhance viscosity, gelation behaviors, and textural characteristics of fruit-based products. These starches differ significantly in their composition, morphology, thermal, rheological, and retrogradation properties, thereby influencing the mechanical and sensory characteristics of the final products (Singh et al., 2003). Corn, wheat, and rice starches exhibit different structural and functional properties, which may influence the texture and mechanical behaviour of the final product. These compositional variations render them suitable for customizing texture in fruit-based products like fruit leathers. In addition to modifying texture, starches and cereal flours influence physicochemical attributes such as colour, water retention capacity, and nutrient preservation. For example, rice flour is often linked to the development of a lighter colour due to its relatively low protein and pigment levels, while corn-based products may display greater firmness and a darker appearance based on processing methods. The significance of these changes is particularly evident in how consumers perceive products, as the visual appeal is a key factor in determining quality for fruit-based snacks. The stability of colour in fruit leathers is significantly affected by the composition of raw materials and the drying processes used. During thermal processing, non-enzymatic browning reactions can occur, resulting in alterations to the L*, a*, and b* values. Consequently, the choice of starch type may indirectly impact colour by affecting water activity and the thermal characteristics of the matrix.

Texture profile analysis (TPA) and tensile tests are commonly employed to assess the mechanical properties of fruit leathers. Key indicators like hardness, chewiness, springiness, and fracturability play crucial roles in shaping consumer perceptions of texture. Alongside physicochemical and textural properties, the mineral composition represents a significant nutritional aspect of fruit-based products. Fruits naturally provide essential minerals like potassium, calcium, magnesium, and trace elements, and the preservation of these minerals during processing is affected by drying techniques and formulation strategies. The addition of cereal-based components may also alter mineral profiles, depending on their inherent composition. Sensory evaluation remains a critical component of product development, encompassing consumer perceptions of colour, flavour, aroma, texture, and overall acceptability. Even when physicochemical properties are optimized, unfavourable sensory attributes may limit product success. Therefore, the integration of instrumental measurements with sensory data is essential for a comprehensive quality assessment of fruit leathers. Within this context, the present study aims to evaluate the effects of different starch and flour sources (corn starch, wheat starch, and rice flour) on the physicochemical, colour, mineral, textural, structural, and sensory properties of orange fruit leather. By integrating multiple analytical approaches, the study seeks to provide a comprehensive understanding of how formulation strategies influence product quality and consumer acceptability. Although fruit leathers have been widely investigated in terms of drying conditions, formulation strategies, and quality attributes, comparative studies focusing on the role of different starch sources within a single fruit matrix remain limited. In particular, the combined evaluation of physicochemical, textural, structural, and sensory properties in starch-modified fruit leather systems is not yet fully elucidated. Therefore, this study aims to systematically investigate the effects of different starch sources on the quality characteristics of orange fruit leather, providing an integrated assessment that links formulation, structure, and functionality. Although the production and quality attributes of fruit leathers made from traditional raw materials such as grape, mulberry, and pomegranate have been extensively studied, literature regarding citrus-based fruit leathers, particularly orange fruit leather, remains scarce. Orange juice presents a challenging matrix for leather formation due to its high organic acid and soluble solid content, necessitating a precise evaluation of structural enhancers. Therefore, this study aims to address this research gap by evaluating.

MATERIAL AND METHODS

Materials

Fresh, fully ripe commercial oranges (Citrus sinensis L. Osbeck, cv. Washington Navel) were purchased from a local market in Aydın, Türkiye, while granulated sugar (Torku Şeker, Konya), rice flour, corn starch, and wheat starch (Dr. Oetker, İzmir) were purchased from a supermarket in Denizli, Türkiye.

Methods

Production of Fruit Leathers

Fresh oranges purchased from a local market were used without any pretreatment other than washing. After washing, the oranges were squeezed using a manual home-type citrus juicer and filtered to obtain the orange juice. According to the formulation presented in Table 1, granulated sugar was added to the orange juices, and the mixture was boiled for 10 minutes. A separately prepared suspension (a mixture of water and starch) was continuously stirred while being added to the boiling sugared orange juice. The mixture was boiled and stirred for an additional 5 minutes to thicken. Subsequently, it was left to cool for 15 minutes. The slightly cooled mixture was poured in a thin

layer onto clean cotton cloths and dried at room temperature for 4 days to produce the fruit leathers. The fruit leather production process was determined according to the method described by Göncü et al. (2022). The drying process was carried out under natural, uncontrolled ambient conditions (approximately 20-25 °C) to simulate traditional fruit leather production practices, as described by Göncü et al. (2022). The fruit leathers were produced in duplicate, and all analyses were performed in triplicate.

Table 1. Formulations of orange fruit leather

Sample*	Orange Juice (mL)	Sugar (g)	Corn Starch (g)	Wheat Starch (g)	Rice Flour (g)	Water (mL)
OFL-CS	1000	275	125	-	-	375
OFL-WS	1000	275	-	125	-	375
OFL-RF	1000	275	-	-	125	375

*OFL = orange fruit leather, CS = corn starch, WS = wheat starch, RF = rice flour.

Analyses

Dry matter analysis of the produced fruit leathers was performed in accordance with AOAC (1990). The fruit leather samples, placed in drying vessels brought to a constant weight, were dried at 105±2°C until the difference between consecutive weighing was 0.2%. Water activity values were determined using a water activity meter at 25°C (FA-st Lab, GBX, Ireland). The thickness of the fruit leathers was measured using a digital micrometer (Mitutoyo, Japan). Protein content was determined using the AACC (1999) Kjeldahl method. The nitrogen conversion factor was accepted as 6.25. Ash analysis was conducted according to the AOAC (1990) method. The pH measurements were obtained by directly immersing the pH meter probe into the slurry (the fruit leather mixture ready for drying). Colour analysis was performed using a Hunter LabScan Colorimeter (HunterLab MiniScan XE, USA). The pH of the initial slurry was measured prior to drying, rather than the final dried product. This approach was chosen because initial acidity is the primary determinant of microbial and biochemical stability during the prolonged room-temperature drying process. Colour values of samples were calculated with L, a and b, Hunter-Lab Mini Scan XE colour meter device (Reston, VA, USA).

For mineral matter analysis, a wet digestion process was applied using a microwave digestion system after adding 10 mL of HNO3 to the fruit leathers. After filtering through filter paper, the samples were analysed using an inductively coupled plasma optical emission spectrometer (ICP-OES, Perkin Elmer, Optima 2100 DV, Massachusetts, USA) to determine the contents of Ca, Fe, K, Mg, Mn, P, and Zn. For the textural properties of the fruit leathers, texture profile analysis and tensile testing were performed using a Brookfield (Model No: CT3-4500, USA) texture analyser. The method described by Tontul and Topuz (2017) was used with modifications. The fruit leathers were cut into dimensions of 5 cm x 10 cm for texture profile analysis and 2.5 cm x 10 cm for tensile testing. In the texture profile analysis measurement parameters, a TA-DE probe, a target value of 0.4 mm, a trigger load of 0.05 N, and a test speed of 2 mm s-1 were used. The tensile test was conducted using a TA-DGF probe with measurement parameters of a 20 mm target value, a 0.05 N trigger load, and a test speed of 2 mm s-1.

For viscosity determination, the consistency index (K) and flow behaviour index (n) values of the prepared slurries were measured using a Brookfield programmable DV-II+ (Middleboro, Massachusetts, USA) viscometer. The sample prepared for analysis was transferred to a sample cup (Brookfield Accessories, SC4-13R) connected to a circulating water bath, and K and n values were determined at 70°C using an SC4-21 spindle (Brookfield Accessories) at 13 different speeds (0.5, 2.5, 5, 10, 15, 20, 30, 40, 50, 60, 80, 100, and 140 rpm). The power-law model was used (Equation 1) to determine the flow behaviour characteristics of slurries (τ: Shear Stress, K: Consistency Index, γ: Shear Rate and n: Flow Behavior Index.). The experimental data were fitted to the Power-law model using Microsoft Excel (Microsoft Corporation, USA). The goodness-of-fit for the mathematical model was assessed using the coefficient of determination (R2), which yielded highly satisfactory values (R2 > 0.98) for all evaluated samples.

Equation 1: $\tau = K \cdot (\gamma)^n$

The surface morphologies of the fruit leathers were examined using scanning electron microscopy (SEM). For this purpose, the samples were precisely cut into small dimensions (approximately 5 x 5 mm) using a sharp surgical scalpel. To minimize potential vacuum interference during imaging, the cut pieces were temporarily stored in a desiccator prior to mounting. Prior to analysis, to gain conductivity, the fruit leathers were mounted onto a carbon stub and then coated with a Gold/Palladium (80:20/w:w) mixture at room temperature (Quorum, Q150R ES, UK).

Images of the samples were taken using SEM (ZEISS, SUPRA 40VP, Germany) at 5kV. The sample images were obtained at a magnification of 5000x.

Sensory analysis was conducted to evaluate the colour, odour, flavour, texture, and overall acceptability properties of the fruit leathers. A total of 19 female and 11 male semi-trained panellists, ranging in age from 19 to 45, participated in the sensory analyses. The sessions took place under standard conditions, and panellists were provided with water and unsalted crackers for palate cleansing between samples. The panellists were presented with fruit leather samples coded with random numbers and asked to evaluate them on a scale from 7 (Excellent) to 1 (Extremely Poor) (Altuğ-Onoğur & Elmacı, 2015).

Statistical Analysis

Each formulation was analysed in triplicate, and the resulting data were subjected to one-way ANOVA followed by Duncan's multiple range test using SPSS Statistics software (IBM Corp., Armonk, NY, USA). Differences were considered significant at $p < 0.05$.

RESULTS AND DISCUSSION

The physicochemical properties of orange fruit leather samples formulated with different structuring agents are presented in Table 2. Significant differences ($p < 0.05$) were observed among formulations for several parameters, indicating that the type of starch/flour markedly influenced product quality.

Table 2. Physicochemical properties of orange fruit leather samples

Sample	Thickness	Moisture content (%)	Water activity	Protein content (%)	Ash content (%)	pH
OFL-CS	2.07±0.10^{b}	20.17±0.11^{b}	0.64±0.01^{b}	1.01±0.08^{a}	0.48±0.01^{a}	3.29±0.01^{a}
OFL-WS	1.74±0.05^{a}	18.72±0.42^{a}	0.63±0.01^{b}	0.99±0.01^{a}	0.52±0.03^{a}	3.29±0.01^{a}
OFL-RF	2.02±0.08^{b}	20.11±0.82^{b}	0.55±0.00^{a}	2.50±0.11^{b}	0.57±0.09^{a}	3.34±0.01^{b}

* Values are expressed as mean ± standard deviation. Different superscript letters within the same column indicate significant differences ($p < 0.05$). OFL = orange fruit leather, CS = corn starch, WS = wheat starch, RF = rice flour.

Thickness of the samples varied between 1.74 and 2.07 mm. The OFL-WS sample had the thinnest measurement at 1.74 mm, while OFL-CS and OFL-RF demonstrated significantly thicker measurements of 2.07 mm and 2.02 mm, respectively. The influence of hydrocolloid type on structural and thickness-related properties has likewise been documented in various fruit-based products (Alam et al., 2025; Alam et al., 2024). Moisture content varied significantly among the samples, ranging from 18.72% to 20.17% (Table 2). OFL-CS and OFL-RF exhibited higher moisture contents (20.17% and 20.11%, respectively) and were not significantly different from each other. In contrast, OFL-WS showed the lowest moisture content (18.72%), indicating a comparatively higher water retention capacity within the matrix. This suggests that wheat starch may promote moisture binding and retention in the gel network, leading to reduced solid matter concentration compared to the other formulations. The ability to retain moisture is an important quality factor that influences texture, microbial stability, and the shelf life of fruit-based products. The water activity (aw) levels ranged from 0.55 to 0.64 (Table 2). OFL-RF exhibited the lowest aw at 0.55, which is significantly lower than that of starch-based samples. Although its overall moisture content was similar to that of OFL-CS, the lower aw indicates that a larger proportion of water was held within the matrix, thus making it less accessible for microbial or chemical activity. Lower aw values are beneficial for enhancing microbial stability and minimizing quality decline during storage. Similarly, previous studies have shown that the selection of hydrocolloid can affect the water activity and overall quality characteristics of fruit leather products (Kurniadi et al., 2022). The amount of protein varied significantly between the samples. OFL-CS and OFL-WS had roughly 1.00% protein whereas OFL-RF had the highest level (2.50%) (Table 2). Increased protein levels may also influence texture and mechanical strength by interacting with polysaccharides to reinforce the structure. Ash content ranged from 0.48 to 0.57%, with no significant differences among samples (Table 2). This indicates that mineral contribution from the structuring agents was relatively limited compared with the dominant fruit matrix. Similar ash levels among formulations suggest that replacing starch type had only a minor effect on total mineral residue. The ash content of fruit leather products is primarily governed by the mineral composition of the fruit matrix, particularly the inherent mineral levels of raw materials. Accordingly, differences in ash content are more strongly associated with formulation composition than with the type of structuring agent used (Kurniadi et al., 2022). The pH values were acidic in all formulations (3.29–3.34) (Table 2), which is characteristic of orange-based products due to the presence of citric and other organic acids. OFL-RF showed a slightly but

significantly higher pH (3.34) than the starch-based samples (3.29).

The rheological characteristics of the orange fruit leather samples were assessed using the Power Law model, and the resulting values for the flow behavior index (n), consistency coefficient (K), and coefficient of determination (R^2) are shown in Table 3.

Table 3. Rheological properties of orange fruit leather samples at different temperatures during forward and backward measurements

Sample	T (ºC)	Forward measurements			Backward measurements		
		n	K (Pa Sn)	R^2	n	K (Pa Sn)	R^2
OFL-CS		0.3568	102.71	0.9956	0.3261	111.05	0.9957
OFL-WS	25	0.3324	89.229	0.9907	0.2562	83.058	0.9901
OFL-RF		0.4194	79.159	0.9972	0.3841	79.373	0.9962
OFL-CS		0.3447	73.952	0.994	0.351	74.867	0.9964
OFL-WS	40	0.378	66.106	0.9923	0.4034	55.43	0.9972
OFL-RF		0.3893	76.567	0.9905	0.3629	67.623	0.997
OFL-CS		0.299	40.521	0.9955	0.3004	36.233	0.9933
OFL-WS	50	0.4294	61.677	0.9954	0.4204	56.598	0.9942
OFL-RF		0.4229	72.029	0.9931	0.3758	66.703	0.9934
OFL-CS		0.3762	32.206	0.9923	0.3877	30.327	0.9982
OFL-WS	70	0.3822	48.575	0.9917	0.3157	53.688	0.9891
OFL-RF		0.4129	64.159	0.9966	0.3779	70.593	0.9973

* OFL = orange fruit leather, CS = corn starch, WS = wheat starch, RF = rice flour.

The high R^2 values obtained for all samples (0.9891–0.9982) indicated that the Power Law model adequately described the flow characteristics of the formulations. The n values for all samples were found to be below 1.0 at every temperature tested, indicating that the formulations demonstrated non-Newtonian pseudoplastic (shear-thinning) behaviour. The low n values (ranging from 0.2562 to 0.4294) obtained for all formulations indicate a pronounced shear-thinning tendency, meaning that the samples became less resistant to flow as the shear rate increased. The consistency coefficient (K), which indicates the viscosity and thickness of the samples, typically decreased with rising temperatures across all formulations. The OFL-CS sample exhibited a significant reduction in K values, decreasing from 102.71 $Pa{\cdot}s^n$ at 25 °C to 32.206 $Pa{\cdot}s^n$ at 70 °C during forward measurements, and similar decreases were noted for the OFL-WS and OFL-RF samples as well. Both forward and backward measurements were conducted to assess the flow characteristics of the samples under conditions of increasing and decreasing shear. The forward measurements represented the rheological response during gradual increases in rotational speed, whereas the backward measurements corresponded to the decreasing rotational speed stage. Minor variations between forward and backward readings indicated slight alterations in structure during shearing.

The colour properties of orange fruit leather samples formulated with different structuring agents are presented in Table 4. Colour is one of the most important quality attributes influencing consumer perception and acceptance, particularly in fruit-based snacks where appearance is often associated with freshness, flavour intensity, and processing

quality. Significant differences ($p < 0.05$) were observed among formulations for all measured color parameters, indicating that the type of structuring agent substantially affected visual characteristics. The lightness (L*) values changed between 59.18 and 63.19 (Table 4).

Table 4. Color properties of orange fruit leather samples

Sample	*L**	*a**	*b**
OFL-CS	59.18±0.01[a]	3.32±0.02[c]	33.34±0.03[b]
OFL-WS	63.19±0.42[b]	-0.32±0.19[a]	33.94±0.18[c]
OFL-RF	62.87±0.08[b]	1.65±0.06[b]	32.63±0.06[a]

* Values are expressed as mean ± standard deviation. Different superscript letters within the same column indicate significant differences ($p < 0.05$). OFL = orange fruit leather, CS = corn starch , WS = wheat starch, RF = rice flour.

Compared to OFL-WS and OFL-RF, which exhibited significantly higher and statistically similar lightness values (63.19 and 62.87, respectively), OFL-CS showed the lowest L* value (59.18), indicating a darker appearance. Lower L* values in fruit-based systems are frequently associated with Maillard reactions caramelization or the thermal breakdown of natural pigments during dehydration. The redness/greenness parameter (a*) revealed notable variations between samples (Table 4). The variations imply that the fruit matrixes pigment stability and colour expression were impacted by the structuring agents. Orange pulps natural carotenoid-related pigments may be better retained or concentrated in OFL-CS due to its more intense red colour. The values for the yellowness parameter (b*) varied from 32.63 to 33.94. OFL-WS had the highest b* value (33.94) followed by OFL-CS (33.34) and OFL-RF (32.63). Higher b* values are typically regarded as advantageous for preserving a natural and appealing appearance because orange fruit products are expected to have strong yellow-orange tones due to carotenoids.

The mineral composition of orange fruit leather samples formulated with different structuring agents is presented in Table 5. Minerals are vital dietary components involved in numerous physiological processes, including skeletal development, enzymatic reactions, neural transmission, and immune system function (Razzaque and Wimalawansa, 2025). The results demonstrated that mineral levels varied according to the type of structuring agent used, indicating that formulation can significantly influence the micronutrient profile of the final product.

Table 5. Mineral composition of orange fruit leather samples (ppm)

Sample	B	Ca	Cu	Fe	K	Mg	Mn	P	Zn
OFL-CS	2.28	209.37	n.d.	25.96	2650.46	303.76	0.13	736.72	0.19
OFL-WS	1.83	276.76	n.d.	28.3	2492.89	274.88	0.25	827.12	1.17
OFL-RF	2.55	352.16	0.14	35.83	2876.98	389.47	1.54	915.68	1.8

OFL = orange fruit leather, CS = corn starch , WS = wheat starch, RF = rice flour, n.d. = not detected.

The most common mineral in all samples was potassium (K) which ranged from 2492.89 to 2876.98 ppm. OFL-RF had the highest potassium content with OFL-CS and OFL-WS following. The higher K level in the rice flour formulation could be a result of the rice flours inherent mineral contribution. Fruit leathers high potassium content makes it more appealing as a nutritious snack option. With values ranging from 736.72 to 915.68 ppm phosphorus (P) was the second most abundant mineral. OFL-RF had the highest phosphorus concentration with OFL-WS and OFL-CS following. The calcium (Ca) content ranged from 209.37 to 352.16 ppm, with OFL-RF again exhibiting the highest value. The mineral density of fruit leather products may be improved by partially substituting cereal flour due to the rice flour formulations comparatively high calcium content. Additionally, OFL-WS exhibited a higher Ca content than OFL-CS, suggesting that wheat starch may contribute more mineral residue compared with corn starch. The levels of magnesium (Mg) another crucial macromineral ranged from 274.88 to 389 47 ppm. Compared to the starch-based formulations OFL-RF had more Mg. Magnesium is necessary for energy metabolism and many enzymatic processes (De Baaij et al., 2015). Cereal flours generally retain more native minerals compared with starches due to the loss of mineral-rich outer fractions during refining processes (Slavin et al., 1997). The iron (Fe) content of trace minerals varied from 25.96 to 35.83 ppm with OFL-RF exhibiting the highest level. Manganese (Mn) increased from 0.13 to 1.54 ppm while zinc (Zn) values increased from OFL-CS (0.19 ppm) to OFL-RF (1.80 ppm). These results show that adding rice flour

considerably enhanced the orange fruit leathers trace mineral profile. OFL-CS and OFL-WS did not contain any copper (Cu) but OFL-RF did contain a detectable amount (0.14 ppm). The values of boron (B) varied from 1.83 to 2.55 ppm with OFL-RF once more having the highest concentration. Boron has been recognized as a bioactive beneficial trace element involved in physiological functions such as bone health, brain function, and immune response (Nielsen, 2008). The predominance of potassium observed in the present study is consistent with previous reports on fruit leather products. For instance, Ayalew and Emira (2020) reported potassium as the major mineral in fruit leather formulations, followed by magnesium and calcium, although the absolute mineral concentrations varied depending on the fruit source and formulation. Similar to the present findings, the authors also demonstrated that formulation ingredients significantly influenced the mineral composition of the final product.

Texture profile analysis (TPA) is one of the most critical quality indicators for fruit leather products as it directly affects consumer perception of chewability, mouthfeel, and overall acceptability. The incorporation of different structural ingredients (corn starch, wheat starch, and rice flour) significantly influenced all texture parameters including hardness, adhesiveness, fracturability, gumminess, and chewiness ($p < 0.05$) (Table 6).

Table 6. Texture profile of orange fruit leather samples

Sample	Hardness (g)	Adhesiveness (mJ)	Fracturability (g)	Springiness (mm)	Gumminess (g)	Chewiness (mJ)
OFL-CS	698.33±59.43^{c}	0.01±0.00^{a}	617.60±51.04^{c}	4.45±0.32^{a}	497.92±43.08^{c}	22.87±4.26^{c}
OFL-WS	297.25±35.42^{b}	0.06±0.01^{b}	297.25±35.42^{b}	4.20±0.24^{a}	196.80±31.55^{b}	9.20±2.98^{b}
OFL-RF	60.05±1.97^{a}	0.12±0.03^{c}	60.05±1.97^{a}	4.25±0.14^{a}	51.76±2.35^{a}	2.16±0.14^{a}

* Values are expressed as mean ± standard deviation. Different superscript letters within the same column indicate significant differences ($p < 0.05$). OFL = orange fruit leather, CS = corn starch , WS = wheat starch, RF = rice flour.

Hardness values showed a marked decrease with the substitution of corn starch by wheat starch and rice flour. The control sample (OFL-CS) exhibited the highest hardness (698.33 g), followed by OFL-WS (297.25 g), while OFL-RF showed a dramatically lower value (60.05 g). This reduction can be attributed to differences in gel network formation and mechanical strength depending on starch type and amylose content, as previously demonstrated in starch-based composite gel systems (Shahsavani and Rafe, 2018). A similar trend was observed for fracturability, which decreased from 617.60 g (OFL-CS) to 60.05 g (OFL-RF) (Table 6). Fracturability is closely related to structural integrity, and lower values indicate a more brittle and easily breakable product. The pronounced reduction in OFL-RF suggests a less dense internal structure. Adhesiveness increased progressively from OFL-CS (0.01 mJ) to OFL-RF (0.12 mJ). This behaviour may be explained by the higher proportion of soluble components and finer particle size of rice flour, which can increase surface stickiness. Springiness values did not differ significantly among samples (4.20–4.45 mm) (Table 6), indicating that elastic recovery was not strongly affected by starch type. This suggests that the basic viscoelastic behaviour of the fruit leather matrix was mainly governed by the fruit pulp–sugar network rather than the added structuring agents. Gumminess and chewiness showed a significant decreasing trend with rice flour incorporation (Table 6). Gumminess dropped from 497.92 g in OFL-CS to 51.76 g in OFL-RF, while chewiness decreased from 22.87 mJ to 2.16 mJ. From a product development perspective, corn starch contributes to the most stable and firm structure, whereas rice flour yields a softer texture that may be preferred for specific consumer groups such as children or elderly individuals. The importance of chewiness for fruit leather quality has also been highlighted in previous studies. Huang and Hsieh (2005) reported that chewiness was among the key textural attributes influencing sensory perception and consumer preference in pear fruit leather products. Therefore, the substantial reduction in chewiness observed in OFL-RF may have contributed to its lower sensory texture score and overall acceptability.

Tensile analysis is a key mechanical indicator for fruit leather products, reflecting resistance to stretching and structural integrity during handling and consumption. As shown in Table 7, significant differences were observed among samples in terms of peak load and work of deformation ($p < 0.05$), while deformation values remained statistically unchanged. These findings suggest that the final texture of the fruit leathers was influenced not only by rheological behavior but also by structural changes occurring during dehydration

Table 7. Tensile analysis results of orange fruit leather samples

Sample	Peak Load (g)	Deformation (mm)	Work (mJ)
OFL-CS	183.83±14.26^{c}	4.94±0.05^{a}	5.50±0.45^{c}
OFL-WS	152.17±12.59^{b}	4.95±0.02^{a}	4.36±0.72^{b}
OFL-RF	45.50±3.63^{a}	4.92±0.04^{a}	1.48±0.23^{a}

* Values are expressed as mean ± standard deviation. Different superscript letters within the same column indicate significant differences ($p < 0.05$). OFL = orange fruit leather, CS = corn starch , WS = wheat starch, RF = rice flour..

Peak load values decreased markedly with the substitution of corn starch by wheat starch and rice flour (Table 7). The highest resistance to tensile force was observed in OFL-CS (183.83 g), followed by OFL-WS (152.17 g), whereas OFL-RF exhibited the lowest value (45.50 g). This pronounced reduction indicates a weaker internal network structure in rice flour-based formulations. Corn starch, with its higher tendency to form rigid gel matrices upon drying, likely contributed to the superior structural resistance observed in OFL-CS. Work of deformation showed a parallel decreasing trend, from 5.50 mJ in OFL-CS to 1.48 mJ in OFL-RF. This parameter reflects the total energy required to break the structure, and its reduction further confirms the formation of a less cohesive matrix in rice flour-enriched samples. In contrast, deformation values did not show significant differences among samples (4.92–4.95 mm) (Table 7), suggesting that extensibility was not strongly affected by starch type. Sensory evaluation plays a decisive role in determining consumer acceptance of fruit leather products, as mechanical and physicochemical improvements must ultimately translate into favourable sensory perception. As shown in Table 8, significant differences were observed mainly in taste, texture, and overall acceptability, while colour and odour scores remained statistically similar among samples ($p < 0.05$).

Table 8. Sensory evaluation of orange fruit leather samples

Sample name	Color	Odor	Taste	Texture	General acceptability
OFL-CS	4.73±0.81a	4.37±0.98a	5.13±1.12b	4.87±1.28b	4.93±0.96b
OFL-WS	4.70±0.78a	4.47±0.81a	5.03±1.33b	4.87±0.99b	4.87±1.12b
OFL-RF	4.57±0.56a	4.40±0.66a	3.90±0.91a	3.27±0.73a	3.77±0.92a

* Values are expressed as mean ± standard deviation. Different superscript letters within the same column indicate significant differences ($p < 0.05$). OFL = orange fruit leather, CS = corn starch, WS = wheat starch, RF = rice flour.

There were no significant differences among the formulations, and colour scores varied only slightly, ranging from 4.57 to 4.73. This implies that replacing corn starch with rice flour and wheat starch did not significantly alter the products appearance. Additionally, there were no significant differences in the odour scores (4.37–4.47) suggesting that orange volatiles rather than structural components were primarily responsible for the perception of aroma. On the other hand, compared to OFL-CS (5.13) and OFL-WS (5.03) taste scores significantly decreased in the rice flour-based sample (OFL-RF) which received the lowest value (3.90). Because structural weakening can affect flavour retention and release dynamics during consumption, this reduction may be explained by the altered mouthfeel and perceived flavour release of OFL-RF. Similar trends were observed in texture scores with OFL-RF exhibiting considerably lower acceptability (3.27) than OFL-CS and OFL-WS (both 4.87). On the other side, OFL-CS received the highest acceptance closely followed by OFL-WS while OFL-RF was much less favoured. General acceptability scores ranged from 3.77 to 4.93. Despite having similar colour and odor characteristics rice flour-based samples have lower overall acceptability due to combined detrimental effects on taste and texture. This suggests that the main factors influencing consumer preference in orange fruit leather goods are mouthfeel and structural integrity. It can be stated that wheat starch can be considered a suitable alternative to corn starch without compromising consumer acceptance, whereas rice flour negatively affects key sensory attributes, particularly texture and taste. Similar differences in sensory properties among

fruit leather formulations have been reported previously (Yadav et al., 2022). SEM micrographs revealed clear differences in the surface morphology of orange fruit leather samples depending on the structuring agent used (Figures 1). The corn starch-based sample (OFL-CS) exhibited a relatively compact and continuous matrix with clustered granular domains embedded within the surrounding phase.

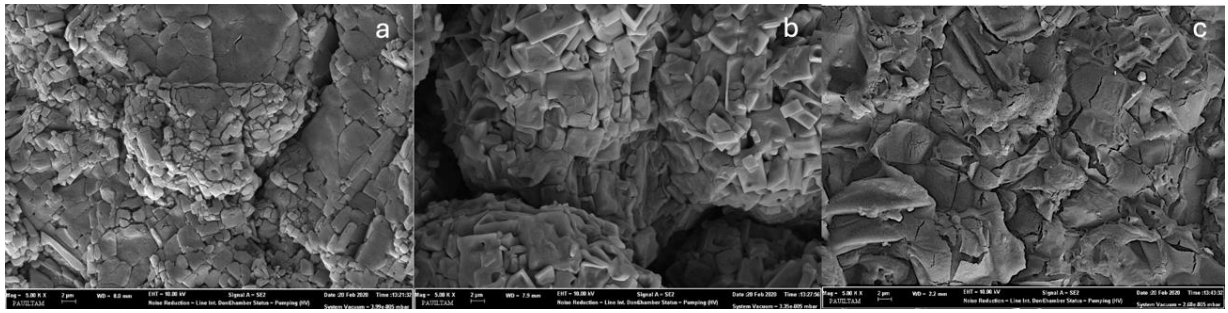


Figure 1. Scanning electron microscopy (SEM) micrograph of corn starch-based orange fruit leather (OFL-CS)[a], wheat starch-based orange fruit leather (OFL-WS) [b] and rice flour-based orange fruit leather (OFL-RF) [c].

This structure suggests effective gelatinization and network formation during drying, which may contribute to improved structural integrity and cohesiveness of the product. The presence of densely packed regions also indicates stronger intermolecular interactions between starch components and fruit solids. Compared with the other formulations, fewer visible cracks and voids were observed in OFL-CS, indicating a more integrated and continuous microstructure. In contrast, the wheat starch-based sample (OFL-WS) showed a more ordered and layered morphology characterized by plate-like structures and a comparatively uniform arrangement. The smoother and more organized matrix may be associated with the swelling and retrogradation behavior of wheat starch fractions during processing. The layered formations produced a relatively homogeneous surface architecture, with fewer fragmented regions than those observed in OFL-RF. The rice flour-based sample (OFL-RF) displayed a rougher and more heterogeneous surface with irregular folds, cracks, and fragmented regions. This less continuous matrix may be attributed to the presence of non-starch components naturally occurring in rice flour, as well as differences in particle size distribution and water-binding behaviour.

CONCLUSION

The current study showed that the quality characteristics of orange fruit leather are greatly influenced by the type of structuring agent. Compared to rice flour, corn and wheat starches improved sensory acceptance mechanical strength and textural stability. On the other hand, even though the mineral and protein content was increased with the addition of rice flour resulted in a softer structure decreased tensile strength and lower sensory scores. Reduced water activity in rice flour samples may be advantageous for microbiological stability but structural weakening outweighed this benefit. Regarding physicochemical, mechanical, and sensory properties, wheat starch demonstrated a well-balanced overall performance. From an industrial standpoint, the results of this research provide valuable insights for the healthy snack food industry. The application of these particular structuring agents reveals a feasible method to standardize textural quality and improve the nutritional content of mass-produced fruit leathers. Future studies should focus on optimizing composite starch systems, particularly through the incorporation of rice flour with hydrocolloids or modified starches, in order to improve structural stability while maintaining nutritional quality. Furthermore, research on microstructural analysis and drying kinetics (e.g. SEM imaging) would offer more comprehensive understanding of matrix formation. The long-term storage stability and shelf-life kinetics of these structured fruit leathers. Additionally, investigating the scalability of these formulations using continuous industrial drying systems rather than traditional methods would provide further value for commercial mass production. Lastly research on consumer acceptance among various age groups may confirm market potential and direct fruit leather product formulation on an industrial scale.

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