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ORIGINAL PAPER

A new plant-based milk and milk powder analogue from apricot (*Prunus Armeniaca* L.) seed press cake after cold pressing process

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Abstract This study explores the potential of apricot seed press cake (APC), a by-product of the apricot processing industry, as a sustainable and functional raw material for the development of high-quality food products. APC was processed into apricot seed milk (ASM) and further processed into protein-enriched apricot seed milk powder (ASMP) by means of spray drying. The results showed that APC contained 49.75% protein, 6.59% fat and 5.3% ash, making it a protein-rich substrate suitable for food applications. ASM exhibited favorable nutritional properties with 8.33% protein, 2.95% fat and 0.81% ash and a distinct volatile profile characterized by 79.15 µg/100 mL benzaldehyde, contributing to its characteristic aroma. However, its L-value (5.14) indicated a lower degree of brightness compared to other plant-based dairy products, indicating the need for advanced processing techniques to improve visual appeal. ASMP exhibited excellent physical properties, including low water activity (0.154) and high protein concentration (38.45%), making it suitable for long-term storage and versatile applications. However, the spray-drying process resulted in a decrease in volatile compound retention, with benzaldehyde content decreasing to 4.11 µg/kg, and had an impact on particle morphology, highlighting the need for process optimization to improve sensory properties and functional performance. This study highlights the importance of apricot seed-derived products in addressing environmental and nutritional challenges. By transforming APCs into functional food ingredients, this research contributes to waste valorization and the growing demand for plant-based, protein-rich alternatives. Future research should focus on optimizing processing conditions and evaluating the health benefits of these products to expand their potential in the food industry.

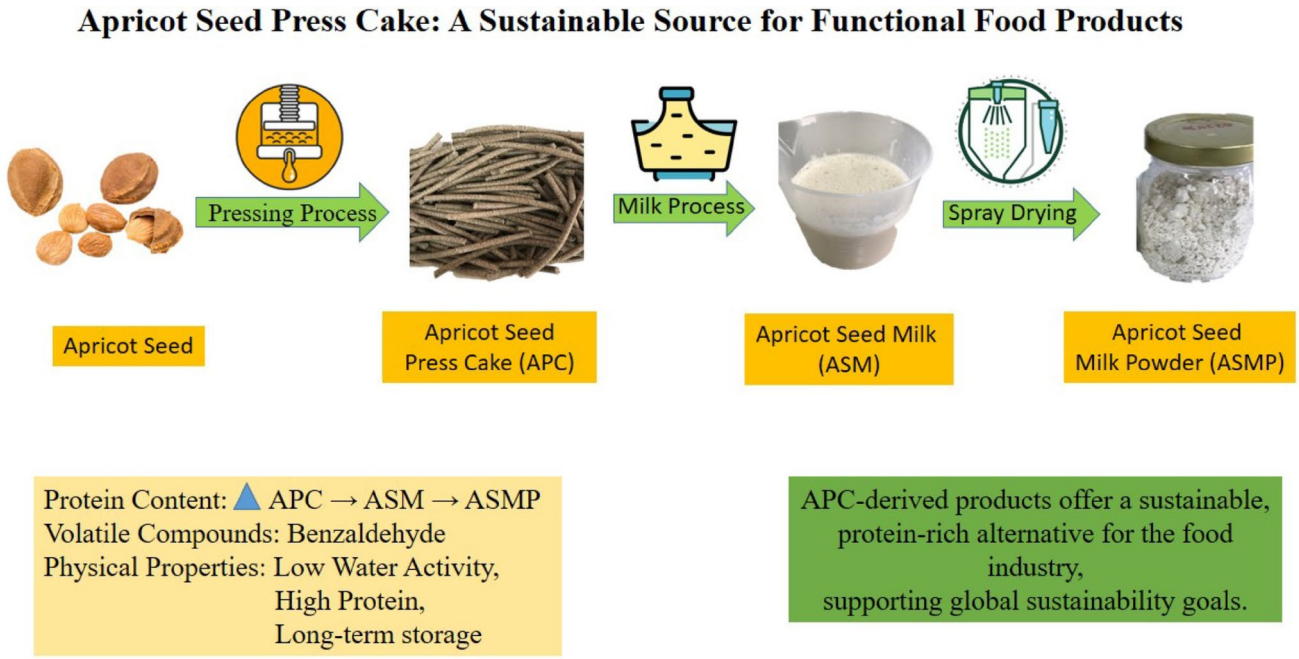
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Graphical abstract



Keywords Apricot seed · Apricot seed milk · Apricot seed milk powder · Spray drying · Waste valorization

Introduction

The increasing demand for plant-based milk and milk powder analogs is due to consumer interest in sustainable, lactose-free and protein-rich dairy alternatives [1]. These products serve as functional food ingredients and offer nutritional benefits such as high protein content, essential fatty acids, vitamins, minerals and bioactive compounds. However, many commercially available plant-based milks, including almond and soy milks, have limitations in protein concentration, sensory properties and functional stability, necessitating the exploration of new plant-based raw materials [2, 3].

A promising but underutilized resource for plant-based dairy alternatives is apricot seed press cake (APC), a by-product of the apricot processing industry [4]. APC is rich in protein (49.75%) and contains essential amino acids and unsaturated fatty acids, making it a valuable ingredient for plant-based milk formulations. Its use is in line with waste valorization strategies that contribute to sustainable food production by converting agricultural by-products into high-quality functional foods [5, 6].

The production of milk from APC represents a new approach to the development of plant-based milk alternatives. Apricot seed milk (ASM) is characterized by a high protein content, essential fatty acids and the absence of lactose, making it a suitable option for people with lactose intolerance and those on a plant-based diet [7]. Spray drying ASM into apricot seed milk powder (ASMP) improves its storage stability and application potential in functional food formulations. While plant-based protein powders have been extensively studied, research on apricot seed milk powder is still limited [8, 9].

This study focuses on the characterization of the physicochemical, sensory and nutritional properties of ASM and ASMP, addressing existing gaps in the literature. In contrast to previous research on plant-based milk powders, this study evaluates the composition, functional properties and potential applications of apricot seed-derived products, expanding the knowledge on alternative protein sources and sustainable food production [10, 11]. By transforming APCs into high-value food ingredients, this research contributes to both waste reduction and the growing demand for plant-based, protein-rich alternatives [12].

In addition, waste valorization plays a crucial role in sustainable food systems as it reduces environmental impact while creating economic value [13]. The conversion of apricot seed press cake into functional milk and milk powder illustrates the potential for innovation in the development of plant-based products [14]. This study aims to highlight the applicability of apricot seed-derived ingredients in food systems and bridge the gap between sustainability, nutrition and functional food development [15].

Materials and methods

Materials

Apricot seeds of the Hacıhaliloğlu variety, which has been recognized as a protected designation of origin (PDO) in Europe since 2017 and belongs to the species *Prunus armeniaca* L., were procured from the apricot market in Malatya province, Türkiye. All chemicals used in the study were of analytical grade and were purchased from Merck (Darmstadt, Germany) or Sigma-Aldrich Co. (USA), unless otherwise stated.

Productions of pressed cake, ASM and ASMP

Apricot press cake (APC) was produced from sulfur-free apricot seeds of the Hacıhaliloğlu variety, which is officially recognized as a protected designation of origin (PDO). The seeds were cold pressed with a Karaerler NF 80 machine (Ankara, Türkiye) equipped with a 7 mm nozzle to extract the oil. The remaining oil-free seeds were labeled as APC. The APC was then ground to a fine powder using a mechanized mortar and homogenized with distilled water at a ratio of 1:5 (w/v) using an Ultra-Turrax homogenizer (IKA Ultra-Turrax T25, Germany). The resulting homogenate was filtered through cloth bags to separate the liquid phase, yielding apricot seed milk (ASM). The filtrate (milk) was collected in glass jars, sealed and stored at 4 °C in the refrigerator until subsequent analyzes and further processing.

The apricot seed milk was pulverized using a laboratory-scale spray dryer (Büchi Mini Spray Dryer, Flawil, Switzerland). During the spray drying process, the air inlet temperature, maltodextrin concentration and aspiration speed were set to 150 °C, 8% and 25 m^3/h, respectively, based on the parameters optimized in preliminary studies. The resulting powder was filled into sterile jars, sealed and stored at 4 °C until further analysis.

Methods

Physicochemical composition

The protein, fat, moisture, and ash contents of the APC, ASM, and ASMP samples were analyzed following the methodologies outlined by Gürkan et al. [15]. A digital pH meter (Mettler Toledo, SevenCompact, S220, Schwerzenbach, Switzerland) was employed to determine the pH values of the samples. The carbohydrate content was calculated using the compositional difference method; i.e., after subtracting the moisture, protein, fat, and ash contents from the total composition.

Color

The color characteristics of ASM and ASMP samples, including L* (lightness), a* (red/green), and b* (yellow/blue) parameters, were evaluated using a colorimeter (Konica Minolta, Chroma Meter CR-5, Kyoto, Japan) following the methodology described by Sahingil and Hayaloğlu [16].

Milk and powder analyses

Physical properties

The hygroscopicity and agglutination degree of the powders were assessed following the procedure outlined by Çalışkan Koç 17]. Additionally, the wettability, spreadability, solubility index, bulk density, compressed bulk density, flowability, and cohesiveness of ASMP were determined using the methods described by Li et al., [18]. These evaluations included physical parameters such as the Carr Index (CI) and Hausner Ratio (HR). Water activity values were measured with a high-precision water activity analyzer (LabTouch, Novasina, Switzerland), featuring a sensitivity of ±0.001.

Particle size

The particle size distribution was measured using a Mastersizer S2000 laser diffraction instrument (Malvern Instruments, Malvern, UK). A small sample of the powder was suspended in isopropanol through magnetic stirring, and the particle size distribution was monitored until consecutive readings stabilized during each measurement. The particle size was expressed as the volume-weighted median diameter, D(V, 0.5), as described by Konstanty and Tyrala [19],.

Microstructure

The microstructure of ASMP was analyzed according to the method described by Alamilla-Beltrán et al. [20]. A scanning electron microscope (SEM) (LEO, EVO 40, Switzerland) was used for this purpose. The powder samples were fixed to aluminum stubs using double-sided adhesive tape. The samples were then coated with gold-palladium and imaged with an ETD detector in the SEM microscope at different magnifications (1,000×, 5,000×, 10,000× and 20,000×).

Individual free amino acid

The levels of free amino acid in ASM and ASMP were determined by the method of Ayag et al. [21] by PITC derivatization. The results are given as µg/mL or mg/g for ASM and ASMP, respectively.

Volatile compounds

The volatile compounds in ASM and ASMP were analyzed using a modified version of the method described by Sulejmani et al. [22] Solid-phase microextraction (SPME) was employed for the extraction of volatile compounds. For the analysis, 3 g of ASM was placed in 15 mL SPME vials, and a 50 ppm solution of 2-methyl-3-heptanone, prepared in 10 µL methanol, was added as an internal standard. A 2 cm divinylbenzene-carboxen-polydimethylsiloxane (DVB-CAR-PDMS) fiber with a coating thickness of 50/30 µm (Supelco, Bellefonte, PA, USA) was used for the extraction. The vials were incubated at 40 °C for 30 min, followed by exposing the SPME fiber to the sample headspace for an additional 30 min to adsorb volatile compounds.

In this study, the analysis of volatile compounds was performed using the SPME-GC-MS method, and the identification was confirmed by comparison with the Wiley 9 and NIST14 mass spectral libraries and by calculation of retention indices (RI) using an n-alkane series (C10–C26). Quantification was performed by external calibration with available standards. Although no odor activity values (OAVs) were calculated in this study, the combination of spectral matching, RI confirmation and quantification with authentic standards ensures reliable identification and comparison of the most important volatiles.

Sensory analysis

The sensory evaluation of apricot seed milk (ASM) and apricot seed milk powder (ASMP) was carried out by a panel of ten semi-trained assessors. The study was conducted in accordance with the Declaration of Helsinki and was approved by the Institutional Review Board (Ethics Committee) of Inonu University (protocol code 7074). All procedures involving human participants were carefully conducted in accordance with the university's ethical principles. The study protocol underwent a comprehensive review and received approval from the university. Informed consent was diligently obtained from all participants before their involvement in the study, ensuring their voluntary participation and a clear understanding of the research objectives. Each sample was evaluated using a unipolar scale based on predetermined sensory attributes. The ASM samples were served in transparent plastic containers at room temperature, while ASMP was evaluated in its original powder form without reconstitution. To minimize order effects, samples were randomly coded and presented in a random order. Panelists were instructed to cleanse their palate with unsalted crackers and mineral water between samples to avoid flavor carryover [24].

The sensory evaluation of ASM focused on five key attributes: Appearance (color intensity and clarity), taste (balance between sweetness and bitterness and aftertaste), aroma (intensity and pleasantness), texture (smoothness, viscosity and creaminess) and overall acceptability. In contrast, the evaluation of ASMP was based on attributes specific to powdered products, including overall acceptability, agglomeration (flowability and homogeneity), color, intensity of apricot kernel flavor, and presence of off-flavors.

Each sensory attribute was rated on a nine-point hedonic scale (1 =extremely bad/unpleasant, 9= excellent/very pleasant). The appearance of ASM was evaluated based on color intensity and clarity, while ASMP was evaluated based on its powder properties. Taste evaluation was conducted exclusively for ASM, focusing on the perception of sweetness, bitterness and aftertaste. The intensity and pleasantness of the flavor were evaluated for both samples. The texture of ASM was evaluated in terms of smoothness, viscosity and creaminess, while for ASMP the flowability of the powder and the tendency to agglomerate were examined. In addition, the flavor intensity of the apricot kernel and the presence of undesirable flavors were investigated for ASMP.

The results of the sensory evaluation provided comprehensive insights into the sensory properties of ASM and ASMP and identified potential areas for quality improvement and increased consumer acceptance.

Statistical analysis

Unless otherwise stated, each experiment was performed in triplicate (n= 3) to ensure statistical reliability and reproducibility of results. Independent replicates were conducted with separate sample preparations and analysis runs according to standardized protocols to minimize variation. The results were expressed as means and standard deviations, which were calculated using Microsoft Excel.

Results and discussion

Physicochemical composition

The chemical composition of APC was determined to be 6.67% moisture, 5.3% ash, 49.75% protein and 6.59% fat (Table 1). In previous studies, hazelnut pulp composition has been found to vary depending on processing and drying conditions. Fan et al. reported that hazelnut pulp contains 25.12% protein, 45.76–62.78% fat, and 3.04% ash, highlighting its high lipid content and potential as a nutrient-rich ingredient [25]. Similarly, Sen and Kahveci [26] found that hazelnut pulp contains 8.3% moisture, 37.3% protein, 9.2%

Table 1 The physicochemical composition for APC

Parameters	Values
Moisture	6.67 ± 0.19
Ash (%)	5.3 ± 0.11
Protein (%)	49.75 ± 1.93
Fat (%)	6.59 ± 0.15
Carbohydrate (%)	31.69 ± 1.38

All data are given as a mean ± standard deviation of three replicates

Table 2 Chemical composition, pH and color values for ASM

Parameters	Values
TDM (%)	12.043 ± 0.04
WSDM (oBrix)	66.33 ± 1.52
Ash (%)	0.81 ± 0.00
Protein (%)	8.33 ± 0.20
Fat (%)	2.95 ± 0.05
pH	6.00 ± 0.00
*L**	51.4 ± 0.52
*a**	15.25 ± 1.13
*b**	8.67 ± 1.03

All data are given as a mean ± standard deviation of three replicates

Table 3 Physical features, chemical composition, pH and color values for ASMP

Parameters	Values
Moisture (%)	2.68 ± 0.08
Ash (%)	3.72 ± 0.18
Protein (%)	38.45 ± 0.47
Fat (%)	2.17 ± 0.011
Carbohydrate (%)	52.98 ± 0.85
pH	6 ± 0.00
Water activity	0.154 ± 0.001
*L**	91.96 ± 0.02
*a**	−0.44 ± 0.01
*b**	0.57 ± 0.01
Wettability (s)	332 ± 2.64
Dispersibility- Diffusibility (%)	65.81 ± 1.98
Resolution index (RI) (%)	74.74 ± 1.48
Bulk density (g/mL)	0.40 ± 0.16
Compressed bulk density, (kg/m3)	0.67 ± 0.30
Fluidity value, CI (%)	30.15 ± 0.06
Stickiness value, HR	1.28 ± 0.04
Hygroscopicity (%)	16.96 ± 0.17
Clumping (%)	27.33 ± 0.18

All data are given as a mean ± standard deviation of three replicates

fat and 5.5% ash. The protein content in APC was higher, while the moisture and fat content was lower than reported in these studies. These differences may be attributed to the more intensive pressing process for apricot seeds, which reduces the fat content [9]. In addition, the differences in raw materials (apricot seeds and hazelnuts) and pressing conditions, such as temperature and nozzle size, may have contributed to the different results [12].

The chemical composition, pH and color values of ASM are shown in Table 2. ASM was found to contain 0.81% ash, 8.33% protein, 2.95% fat, pH 6, 12.043% total solids and 66.33 (Brix). A study on hazelnut milk reported that it contains 2.2–2.5% protein, 6.3–7.3% fat, and a comparable ash content, suggesting its potential as a nutrient-rich plant-based alternative to dairy milk [27]. The higher fat and lower protein content in hazelnut milk compared to ASM could be explained by the lack of a pressing process in the production of hazelnut milk. The lack of pressing preserves the natural fat content of the hazelnuts, which leads to lower protein concentrations. Different ash, protein and fat contents were found in the production of soy milk and almond milk. Soy milk had ash, protein and fat contents of 0.43–0.87%, 1.273–3.240% and 0.763–2.347%, respectively, while almond milk contained 1.63–3.02% ash, 0.768–1.380% protein and 3.833–8.257% fat [28] Compared to ASM, the lower ash, protein and fat contents in these plant-based dairy products are due to the higher dilution rates during production [29]. The pH of ASM (6.0) is consistent with findings in the literature for plant-based milks such as soy and almond milk, which tend to have a similar pH range [29]. This pH is important as it contributes to the stability and sensory properties of plant-based milk [28].

The chemical composition of ASMP was determined to be 2.68% moisture, 3.72% ash, 38.45% protein, 2.17% fat, pH 6 and a water activity of 0.154 (Table 3). Jinapong et al. [30] produced soymilk powder using a spray drying process and reported the following compositional parameters: 48.79% protein, 28.77% fat, 4.97% ash and 4.45% moisture. Compared to ASMP, the soy milk powder had a higher protein content. This difference could be attributed to the biochemical composition of soybeans compared to apricot seeds as well as the potential loss of some protein fractions during the pressing process of apricot seeds [9, 12]. In addition, spray drying parameters such as temperature and maltodextrin concentration can affect the final composition of the powder [30]. The low water activity (a_v) of ASMP (0.154) significantly reduces microbial growth and enzymatic activity, improving microbial stability and extending shelf life. This makes ASMP suitable for long-term storage under ambient conditions and minimizes the risk of spoilage and quality degradation [29].

The chemical and physical properties of ASM and ASMP have been significantly influenced by the type of raw material, processing methods and production parameters. Since ASMP was analyzed in its reconstituted form, the dilution factor (10% w/v) was also taken into account when interpreting the results. While ASM retained its natural composition, ASMP showed slight variations in viscosity and total solids content due to the reconstitution process. However, the overall trends in nutritional composition and

sensory properties remained the same, confirming that the observed differences are primarily due to processing effects and not dilution artifacts. These results underline the high nutritional value and application potential of apricot seed-derived products in various food systems.

Color

Colorimetric analysis (L^*, a^* and b^*) provided an objective measurement of the visual properties of ASM and ASMP. However, the sensory evaluation was performed independently, and the panelists assessed the color subjectively based on their perception under standardized lighting conditions. Although the instrumental color values provide precise quantitative data, no direct correlation analysis was performed between these measurements and the sensory panel scores.

Color is a key attribute that influences consumer preferences for plant-based milk alternatives, as it directly affects the visual appeal and perceived quality of the product. The colorimetric values for ASM and ASMP are shown in Tables 2 and 3. For comparison, the L^* (lightness) value of cow's milk was reported to be 81.89, indicating high opacity and gloss [31]. In contrast, ASM had a significantly lower L^* value of 5.14, indicating lower brightness and a more opaque appearance. Similar studies with other plant-based dairy products showed L^* values of 56.62 for peanut milk [1] and 64.38 for almond milk [32]. Hazelnut milk, on the other hand, had an L^* value of 83.4, comparable to cow's milk [29].

The significantly lower L^* value of ASM compared to other plant-based milks can be attributed to the unique composition of apricot seeds and the specific processing methods. The higher protein concentration in apricot seeds likely contributes to a denser and less translucent matrix, which reduces lightness [2]. In addition, the lack of filtration processes such as centrifugation or homogenization, which are common in the commercial production of plant-based milk, may result in higher particle content and lower optical clarity [32]. To improve the brightness and visual appeal of ASM, future studies could investigate advanced processing methods such as high-pressure homogenization or ultrasonic treatment [29].

For ASMP, the L^*, a^* and b^* values were measured as 91.96, −0.44 and 0.57, respectively, indicating a bright and neutral colored powder. In comparison, camel milk powder had a^* and b^* values of −1.49 and 9.00, respectively, indicating a higher intensity of yellow coloration due to the sugar composition [33]. The lower a^* and b^* values for ASMP could be related to the differences in the composition of the raw material and the lower sugar content in apricot seed-based products. Sugar content is a known determinant of Maillard reactions during spray drying, which can influence the final color of powders [33]. In addition, the protein-rich composition of ASMP likely contributes to the lower yellow coloration (b^* value), as proteins typically have a more neutral coloration compared to carbohydrates or fats [29].

The differences in color parameters between ASM, ASMP and other plant-based dairy products illustrate the influence of raw materials and processing techniques. The lower L^* value for ASM indicates that further optimization of processing conditions is required to improve visual quality. Techniques such as high pressure homogenization or fermentation could increase brightness and uniformity by reducing particle size and improving dispersion of protein and fat components [29]. In contrast, the high whiteness of ASMP ($L^* = 91.96$) demonstrates the effectiveness of spray drying in producing visually appealing powders. However, the variations in parameters such as a^* and b^* indicate that further investigation of drying conditions and sugar-protein interactions during spray drying is required [30, 32].

In summary, the color parameters of ASM and ASMP reflect the interaction of raw material properties and processing methods. While ASM has a lower brightness compared to other plant milks, advanced processing techniques could improve visual quality and consumer acceptance. The high brightness and neutral color of ASMP make it a suitable ingredient for various food formulations. Future studies should focus on optimizing production conditions to further improve the visual and sensory properties of apricot seed-based products.

Physical properties of ASMP

The physical analysis of ASMP included parameters such as wettability, spreadability, solubility index, bulk density, compressed bulk density, flowability, cohesiveness, hygroscopicity and clumping. The results showed that ASMP had a wettability of 332 s, a spreadability of 65.81%, a solubility index of 74.74%, a bulk density of 0.40 g/mL, a compressed bulk density of 0.67 g/mL, a flowability (Carr index, CI) of 30.15%, a cohesiveness (Hausner ratio, HR) of 1.28, a hygroscopicity of 16.96% and a clumping of 27.33% (Table 3).

The wettability, a key property that indicates how quickly a powder disperses in a liquid, varies considerably between the plant-based milk powders. For almond milk powder, wettability values of 13–22 s were reported [34]. In comparison, spray-dried soy milk showed values between 57 and 308 s [30],, goat milk powder between 418 and 594 s [35], yogurt powder between 307 and 756 s [36] and coconut milk powder 722 s [37]. The wettability value for ASMP was higher than that of almond milk powder, but within the

range observed for other spray-dried products. The longer wettability time for ASMP can be attributed to the surface properties and hydrophobic interactions of the proteins in the powder [34]. Optimizing the particle surface modification or increasing the ratio of carriers such as maltodextrin could potentially improve wettability in future studies [38].

Hygroscopicity measures the ability of a powder to absorb moisture from the environment and is directly related to its physical stability and shelf life. The hygroscopicity value for ASMP was 16.96%, which was higher than for almond milk powder 7.7–8.10% [36], babassu coconut milk powder (6.98–9.86% [39] and pequi powder 10.7–14.3% [37]. Higher hygroscopicity values indicate lower physical and storage stability, implying that ASMP is more sensitive to ambient humidity. This finding emphasises the need for controlled storage conditions to maintain the stability of ASMP. The use of carriers such as maltodextrin during spray drying has been shown to reduce hygroscopicity and improve physical stability [30].

Bulk density is a key parameter that influences the packaging and transportation efficiency of powdered products. For ASMP, the bulk density was 0.40 g/mL, and the compressed bulk density was 0.67 g/mL. Compared to almond milk powder, which has a bulk density of 0.30–0.32 g/mL and a compressed bulk density of 0.54–0.56 g/mL [34], ASMP had slightly higher values. The bulk density of ASMP was also higher than that of soy milk powder 0.21 g/mL [30] and comparable to avocado powder 0.37–0.49 g/mL [40]. Yulistiani et al. reported that spray-dried coconut milk powder had a bulk density of 0.38 g/mL and a compressed bulk density of 0.61 g/mL [36]. Compared to these values, ASMP exhibited a slightly higher bulk density, which suggests that its particles may have a more compact structure, likely due to its higher protein content and lower fat content. The differences in bulk density can be attributed to the composition of the raw material, especially the protein content, fat content, and spray drying conditions [34]. The higher protein content and lower fat content in ASMP may have contributed to its slightly higher bulk density compared to almond and soy milk powder, while its values remain comparable to those of coconut milk powder. The physical properties of ASMP differ from those of other plant-based milk powders in the literature due to the unique composition of the apricot seed press cake, the spray-drying parameters and the ratio of carriers. The high hygroscopicity of ASMP suggests that careful storage conditions are required to maintain physical stability. Future studies could focus on optimizing the formulation and drying conditions to improve wettability, reduce hygroscopicity and increase the overall functionality of ASMP. These results underline the potential of apricot seed milk powder as a versatile ingredient in the food industry.

Particle size

The particle size distribution of apricot seed milk powder (ASMP) was analyzed to evaluate the impact of washing solvents (water and 2-propanol) on its physical characteristics. The median particle size [d(0.5)] varied significantly between the two treatments, with water-washed samples exhibiting a value of 0.574 µm, compared to 7.635 µm for 2-propanol-washed samples. The span values, representing the width of particle size distribution, were 22.099 for water-washed samples and 3.389 for 2-propanol-washed samples. These findings suggest that 2-propanol-washed samples had a narrower particle size distribution, leading to improved flow properties.

The specific surface area (SSA), calculated as the total particle surface area per unit weight, was significantly higher in water-washed samples (35.7 µm) compared to 2-propanol-washed samples (14.3 µm). This indicates that water-washed particles have a larger active surface area, which may enhance their dissolution and reconstitution properties. Uniformity values were 7.7 for water-washed and 1.16 for 2-propanol-washed samples, with lower uniformity values suggesting particle sizes closer to the median. The particle size distribution of ASMP was strongly influenced by the choice of washing solvent. Water-washed samples demonstrated smaller particle sizes and higher SSA, which are advantageous for dissolution and reconstitution applications. Conversely, 2-propanol-washed samples exhibited a narrower particle size distribution and superior flowability, indicating that the solvent type plays a crucial role in determining the functional properties of powdered products.

When compared to literature findings, the particle size characteristics of ASMP were found to differ significantly. For instance, Dantas et al. [40] reported median particle sizes ranging from 11 µm to 34 µm for avocado powder produced via spray drying under varying conditions. Similarly, Estrada et al. [41] observed particle size distributions for guacamole powders, with D10 values ranging from 4.1 to 24.9 µm, D50 values from 24.9 to 177.9 µm, and D90 values from 95.0 to 1130.7 µm. These differences are likely due to variations in raw materials, drying techniques, and the solvents used during analysis. Furthermore, the particle size of spray-dried powders is known to depend on atomization parameters, atomizer type, and the physicochemical properties of the feed material, as well as its solid content [42]. These factors underline the importance of considering material and process variations when comparing particle size distributions across studies.

Particle size distribution plays a crucial role in determining the functional properties of plant-based milk powders such as ASMP. Finer particle sizes improve solubility and sensory properties, making them desirable for beverages

and dairy alternatives. Larger particles, on the other hand, improve flowability and stability, which can be beneficial in applications such as baked goods and food supplements. These results show the importance of optimizing particle size for certain food applications.

Microstructure

The ASMP produced with a spray dryer had an irregular structure with particles of different sizes and a high degree of clumping (Fig. 1). The powder appeared to consist of agglomerates formed from very small particles rather than individual, discrete particles. Such agglomeration is usually attributed to the presence of surface-free fat or protein and the formation of water bridges between the particles, which contributes to the cohesive properties of the powder [40]. Cohesiveness is a critical parameter that affects the flowability and reconstitution properties of the powder, which requires careful optimization during production and storage. To ensure a meaningful comparison of the SEM images, both localized zoom images and overall structural views at constant magnification were analyzed. The morphological differences before and after spray drying were evaluated to determine changes in particle size, surface texture and agglomeration behavior. Figure 1 shows a comparative analysis of APC (before processing) and ASMP (after processing) and illustrates the structural change caused by spray drying. The differences in morphology highlight the importance of the processing parameters in determining the final physical properties of the powder, particularly in terms of particle distribution and porosity.

A study investigating the drying of sugar cane juice and whey concentrate solutions showed significant differences in powder morphology depending on the drying temperature. Powders dried at higher air temperatures showed a stronger tendency to disintegrate than those dried at lower temperatures. This phenomenon was associated with the increased vapor pressure at higher temperatures, which caused membrane rupture and led to increased bulk density [43]. In the current study, the SEM images of ASMP are similar to those of powders prepared at high temperatures, suggesting that the drying temperature plays an important role in influencing particle morphology. However, differences in the composition of the raw material, particularly protein and fat content, may also have contributed to the observed morphological variations [29, 34].

The use of maltodextrin as a carrier in ASMP production also appears to influence particle morphology and increase cohesiveness. Maltodextrin increases the viscosity of the starting solution, which affects the formation and distribution of particles during the spray drying process [33]. Higher viscosity leads to irregular particle shapes and more clustering, which is consistent with the observations in this study. In addition, maltodextrin encapsulates surface lipids and proteins, reduces stickiness and forms a stable film around the particles, which can improve the stability and flowability of the powder [35, 38].

Particle size distribution and surface morphology are key factors that determine the reconstitution behavior of powders. Smaller particles with larger surface areas tend to form clusters due to increased surface interactions, especially in the presence of free fat or water bridges [36, 37]. The cohesiveness observed in ASMP can limit flowability and handling properties. This problem could be addressed by optimizing spray drying parameters or adding flow-promoting agents such as silica or tricalcium phosphate to the formulation [30, 40].

The drying temperature and the composition of the starting material also affect the porosity of the particles, which has a significant influence on the solubility and wettability of the powder. Porous particles produced at lower temperatures improve solubility and reconstitution due to increased water absorption. In contrast, higher drying temperatures, as proposed in the ASMP manufacturing process, lead to

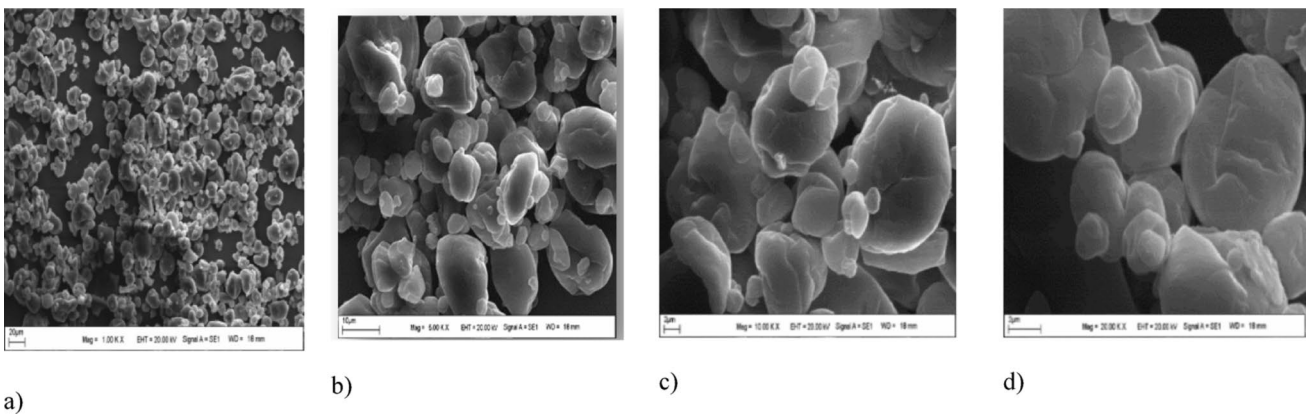


Fig. 1 Scanning electron microscopic images of ASMP. (a) Images (1000 × magnification), (b) Images (5000 × magnification), (c) Images (10000 × magnification) (d) Images (20000 × magnification)

denser particles with lower porosity, potentially limiting these properties [34, 43]. Future studies should investigate the effects of lower drying temperatures and alternative carriers on particle morphology and functional properties to optimize ASMP for different food applications.

Free amino acids

The free amino acid values of ASM and ASMP are shown in Fig. 2. The analysis of the free amino acid content of ASM and ASMP underlines their potential as rich sources of essential and non-essential amino acids. Leucine (Leu) was identified as the most abundant amino acid in ASM with a concentration of 31.73 µg/mL, while threonine (Thr) was detected at the lowest concentration (1.21 µg/mL). In ASMP, Leu was also the most abundant amino acid (238.09 mg/g), while phenylalanine (Phe) had the lowest concentration (10.92 mg/g). It is noteworthy that alanine (Ala) and proline (Pro) were not detected in either ASM or ASMP. This amino acid profile is consistent with the results of studies on other plant protein sources, further supporting the protein richness of apricot seed-derived products [44, 45].

The high content of essential amino acids in ASM and ASMP is particularly noteworthy as they play an important role in muscle protein synthesis and overall health. Essential amino acids (Cys, His, Ile, Leu, Lys, Met, Phe, Thr, Tyr and Val) accounted for 59% and 60.82% of the total amino acids in ASM and ASMP, respectively, with Leu being the most represented. Leu is well documented for its role in activating the mTOR signaling pathway, which promotes muscle protein synthesis, making it a valuable ingredient for functional foods targeting muscle health [46]. These findings suggest that ASMP could be an excellent protein supplement for athletes or individuals in need of high-quality protein intake.

Apricot kernel milk and milk powder (ASM and ASMP) exhibit a notably rich amino acid profile, particularly in terms of glutamic acid (Glu), aspartic acid (Asp), and arginine (Arg), when compared to other plant-based milk and milk powders. The study conducted by Merzlov et al. analyzed almond, rice, coconut, and oat milks, identifying oat milk as the most enriched in essential amino acids among plant-based alternatives; however, deficiencies in methionine and lysine were observed [47]. Furthermore, Singh-Povel et al. reported that soy milk was the only plant-based milk that fully met the World Health Organization (WHO) amino acid requirements, whereas almond, rice, and coconut milks were found to be insufficient due to their low protein content [48]. In this context, apricot kernel milk, with its high Glu (32.32%) and Asp (11.2%) content, appears to be a competitive alternative to oat and soy milk, while also meeting WHO recommendations for essential amino acids. When evaluated in powdered form, Tian et al. demonstrated that spray-dried oat milk powder (OMP) retained a superior nutritional profile compared to commercial soy milk powder, particularly in its ability to preserve essential

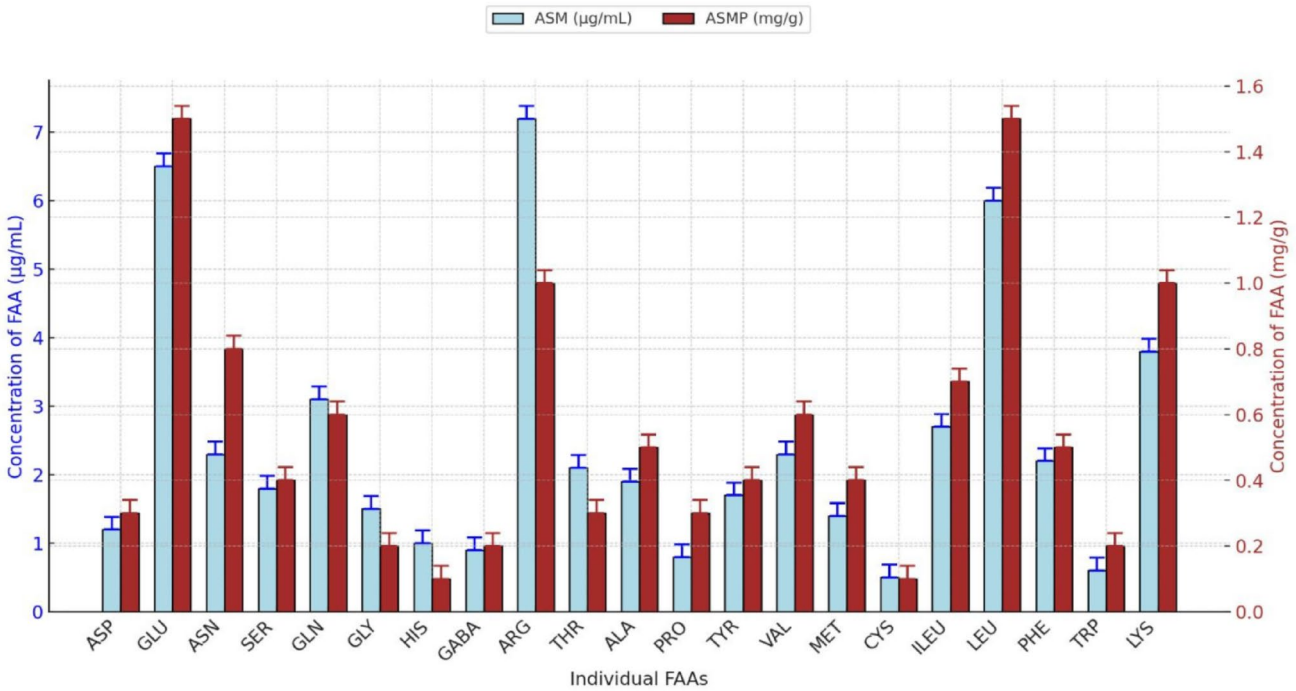


Fig. 2 Levels of free amino acid amounts obtained for ASM and ASMP. Note: To facilitate comparison, µg/mL values (for ASM) can be approximately converted to mg/g (for ASMP) by considering the density of the liquid sample and the dilution factor used in powder analysis. Assuming a density of X g/mL for ASM and a dilution factor of Y mL/g for ASMP, the values can be adjusted accordingly

Table 4 Volatile compounds in ASM

RI	Volatile Compounds	µg/100 mL milk
1080	Hexanal	1.54 ± 0.024
1188	l-Limonene	0.36 ± 0.010
1208	1-Butanol	0.21 ± 0.015
1289	Octanal	0.031 ± 0.016
1397	Nonanal	0.28 ± 0.060
1508	Decanal	0.032 ± 0.004
1540	Benzaldehyde	79.15 ± 10.380
1562	1-Octanol	0.075 ± 0.005
1606	Mandelic Acid	3.96 ± 0.390
1656	1-Nonanol	0.042 ± 0.003
1884	Benzyl Alcohol	1.78 ± 0.038
1923	Phenylethyl Alcohol	0.95 ± 0.087

RI Retention Index

Table 5 Volatile compounds in ASMP

RI	Volatile Compounds	µg/kg powder
966	2-Pentanone	2.90 ± 0.3800
1075	Hexanal	0.38 ± 0.0050
1166	Heptanal	0.53 ± 0.0610
1193	Limonene	2.90 ± 0.2300
1212	Eucalyptol	0.23 ± 0.0220
1225	4-Octanone	0.17 ± 0.0002
1267	Butanoic Acid	0.23 ± 0.0140
1288	1-Pentanol	0.23 ± 0.0007
1394	Nonanol	1.10 ± 0.0600
1484	2-Propanol	0.65 ± 0.0160
1534	Benzaldehyde	4.11 ± 0.200
1541	Linalool	1.10 ± 0.035
1884	Benzyl Methanol	1.10 ± 0.03
1924	Benzyl Ethanol	0.42 ± 0.015

RI Retention Index

amino acids [49]. These findings suggest that apricot kernel milk powder, given its high protein and amino acid content, stands out among plant-based milk powders as a superior alternative.

The differences in amino acid content between ASM and ASMP can be attributed to the physical processes used in their production. For example, the drying process in ASMP production could concentrate certain amino acids, while others may be degraded due to heat sensitivity [50]. In addition, the differences in amino acid profiles reported in other studies could be due to differences in the apricot seeds used, which are influenced by factors such as climate, soil characteristics and cultivation practices. Apricot seeds grown in nutrient-rich soils or under optimal climatic conditions are likely to have better amino acid profiles, as observed in other studies on plant proteins [51].

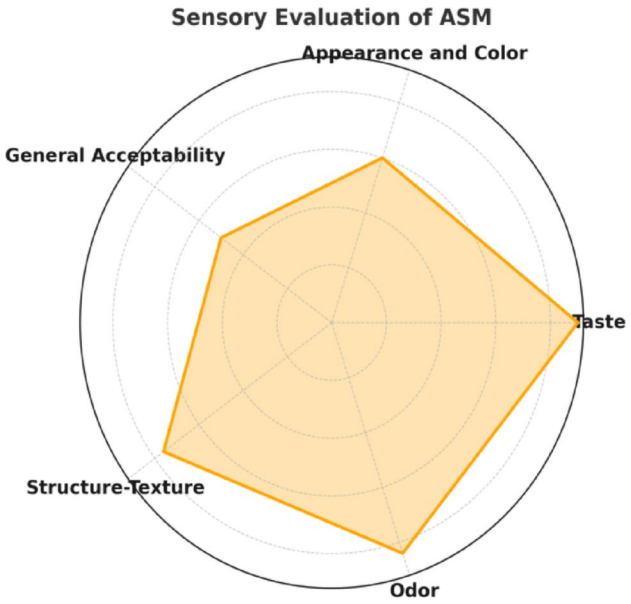


Fig. 3 Sensory evaluation of ASM

Volatile compounds

In this study, ASM was found to contain 11 volatile compounds, with benzaldehyde being the predominant compound at 79.15 µg/100 mL, while octanal had the lowest concentration at 0.03 µg/100 mL (Table 4). In ASMP, 14 volatile compounds were identified, with benzaldehyde again being the most abundant at 0.41 µg/kg and 4-octanone the least abundant at 0.01 µg/kg (Table 5).

Benzaldehyde, a key aromatic compound in apricot seeds and almonds, contributes significantly to the flavor of beverages. In addition to benzyl alcohol, it is also used in therapeutic applications such as the treatment of asthma, bronchitis, emphysema and COPD and is a common ingredient in cough syrups [52]. The higher concentration of benzaldehyde in ASM compared to ASMP is probably due to the less intensive processing of the liquid form. The spray-drying process used in the production of ASMP, which involves high temperatures, can degrade volatile compounds, resulting in them being less detectable in the powder form [52, 53].

The prevalence of benzaldehyde in ASM and ASMP is consistent with previous studies on apricot seed-derived products. Zhang et al. [47] reported 22 volatile compounds, including aldehydes, esters, alcohols, and benzene derivatives, in flavored beverages produced from apricot seed wastewater. Benzaldehyde was the most abundant compound in their study (78.77%), followed by benzyl alcohol (14.61%). The differences in other volatile compounds between ASM and ASMP and the beverages in the Zhang et al. [54] study may be attributed to the process used to remove the bitter compounds from the apricot seeds. The

chemicals used in this process can alter the volatile profile of the final product. This shows how sensitive volatile compounds are to different processing methods.

In addition to their aromatic properties, benzaldehyde, benzyl alcohol and phenylethyl alcohol also exhibit functional health benefits. These compounds have been reported to possess antimicrobial, antioxidant and anti-inflammatory [52]. For example, benzaldehyde and benzyl alcohol are known to support immune function and relieve respiratory symptoms. Beverages prepared from apricot seeds could therefore serve not only as flavorful beverages, but also as functional drinks with potential health benefits, similar to cough syrups.

To improve the preservation of aroma compounds in ASM and ASMP, future studies should focus on optimizing the spray drying process, such as the use of lower inlet temperatures and the inclusion of carriers such as maltodextrin, which have been shown to protect volatiles during drying [35]. In addition, the effects of different apricot seed processing techniques, such as soaking or enzymatic treatments, on the volatiles profile should be thoroughly investigated in order to develop products with improved sensory and functional properties.

The volatile composition of apricot seed milk (ASM) and apricot seed milk powder (ASMP) significantly influences their sensory properties and contributes to their overall flavor profile. The key volatile compounds identified in ASM and ASMP have different aromatic properties that play a crucial role in the perception of these plant-based products:

Benzaldehyde (almond, marzipan aroma): As the dominant aromatic compound in apricot seeds and almonds, benzaldehyde is primarily responsible for the characteristic nutty and marzipan-like flavor of ASM and ASMP [55].

Hexanal (green, grassy, fresh scent): Hexanal is a product of lipid oxidation and contributes to a fresh, green aroma that enhances the perception of freshness in plant-based dairy alternatives [56].

Limonene (citrus, orange-like aroma): A naturally occurring terpene in apricot seeds, limonene provides a subtle citrus note that complements the nutty undertones of ASM [57].

1-Butanol (alcoholic, slightly sweet aroma): This compound is associated with mild alcoholic and fruity notes that can be produced by fermentation processes during processing [58].

Nonanal (floral, fatty, orange peel-like aroma): Nonanal is known for its mild floral and fatty odor and contributes to the smooth aromatic profile of plant-based dairy alternatives [59].

Octanal (citrus, fatty, slightly sweet aroma): Imparts a fruity, citrus-like note that enhances the overall flavor complexity of ASM [60].

Benzyl alcohol (mildly sweet, floral fragrance): Benzyl alcohol is an important aromatic component in apricot seed-based products and imparts a soft floral sweetness [61].

Phenylethyl alcohol (rose, floral aroma): This compound, commonly found in plant sources, enhances aromatic complexity through its sweet and floral properties [62].

Benzaldehyde has been identified as the most abundant volatile compound in both ASM and ASMP and imparts a dominant almond-like aroma to these formulations [55]. However, the significantly higher concentration in ASM compared to ASMP indicates that the processing intensity directly influences the aroma binding. The spray-drying process, which exposes the products to elevated temperatures, likely contributes to the partial volatilization or degradation of benzaldehyde and other important volatile compounds [59]. Similar results have been reported for other plant-based milk alternatives such as almond and tiger nut-based beverages, where heat treatment resulted in significant aroma loss [56].

The decrease in volatile compound content in ASMP highlights the challenges associated with spray drying in aroma preservation [60]. A similar decline in aroma intensity has been documented in other heat-treated plant-based beverages where excessive heat exposure led to evaporation or degradation of key aromatic components [61]. To mitigate these effects and improve the preservation of volatile components, future research should investigate the following aspects: Optimization of spray drying conditions through lower inlet temperatures to minimize thermal degradation. Inclusion of protective carriers such as maltodextrin or gum arabic, which have been shown to encapsulate and stabilize volatile compounds during drying. Use of microencapsulation techniques to improve flavor retention and extend the shelf life of plant-based milk powders [62].

Analysis of the volatile profile of ASM and ASMP revealed that benzaldehyde is the predominant compound responsible for their characteristic nutty and almond-like aroma. The observed reduction in volatile compounds after spray drying indicates that aroma loss is a critical challenge in the development of plant-based milk powders. Further optimization of processing conditions, including the use of alternative drying technologies and encapsulation strategies, is necessary to improve the sensory and functional properties of ASMP. In addition, the potential health benefits of benzaldehyde, benzyl alcohol and other bioactive volatile compounds highlight the multifunctional properties of apricot seed-derived products, not only as flavoring agents but also as functional food ingredients with antimicrobial and antioxidant properties [63].

Future research should focus on evaluating alternative processing methods for apricot kernels, such as enzymatic treatment or controlled fermentation, to further refine the

aroma profile and optimize the sensory appeal of ASM and ASMP for broader commercial applications.

Sensory analysis

After preparation of ASM, it was pasteurized at 85 °C for 15 min and stored in 100 mL jars. After a 24-hour cooling period, a sensory evaluation was carried out by 10 panelists. The results of the sensory analysis (Fig. 3) revealed scores of 3.6 for appearance and color, 4.0 for taste, 4.3 for odor, 4.3 for structure/texture, and 4.1 for overall acceptability. These results indicate that ASM was satisfactory from a sensory perspective, particularly in terms of texture and odor, which scored the highest of all attributes evaluated.

The relatively low score for appearance and color (3.6) is in line with previous research indicating that plant milk often has lower visual appeal compared to animal milk due to its lower brightness and natural color tones [57]. Such visual characteristics can influence consumer perception and acceptability, emphasizing the importance of improving the appearance of ASM. Potential enhancements could include processing methods such as microfiltration or fortification with natural color enhancers such as turmeric or carrot extracts, which have been shown to improve the visual characteristics of plant-based products [52].

The taste score of 4.0 shows that acceptance is satisfactory, but also that there is still room for improvement. According to Cardello et al. [64] plant-based milks, including those made from almonds, cashews and Brazil nuts, typically have a unique flavor profile, such as a salty or earthy flavor, which may not align with consumer preferences for dairy alternatives. To counteract this, the addition of flavor-enhancing substances such as cocoa, vanilla or natural sweeteners has been proposed as an effective strategy to improve the taste of plant-based milks [53]. Such additives can increase the flavor complexity of ASM, making it more appealing to a wider range of consumers.

In the sensory evaluation of ASMP (Fig. 4), subjects gave average scores of over 4.0 for aggregation, color, apricot seed flavor intensity and overall acceptability, indicating a very positive perception of these attributes. The high scores for aggregation and flavor intensity indicate that the spray-drying process effectively preserved the physical and sensory properties of the apricot seed milk powder. However, the "off-flavor" attribute received a score just below 4.0, indicating that some panelists perceived an off-flavor that could be attributed to the residual volatiles present in the apricot seed press cake.

The results are consistent with previous studies indicating that some plant-based protein powders have an off-flavour due to the presence of certain volatile and non-volatile compounds. Phenolic compounds can contribute to bitterness and astringency, while free fatty acids can lead to rancid or soapy notes. These naturally occurring components influence the sensory profile of ASMP, and their effects can be mitigated through processing and formulation strategies [65].

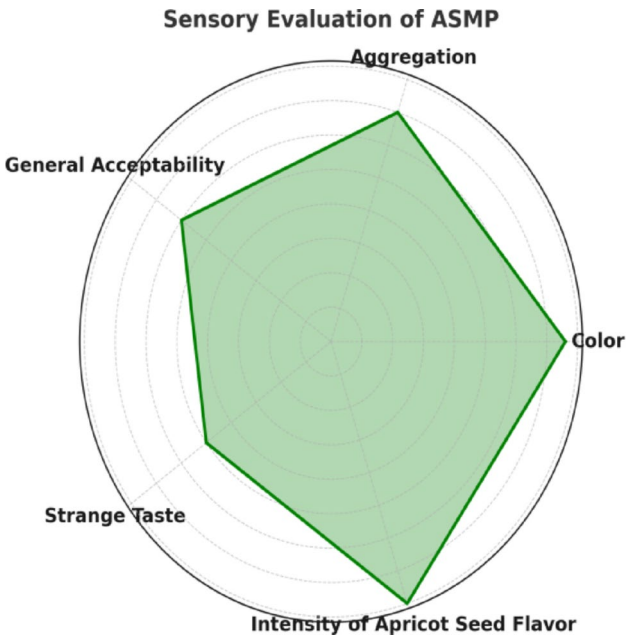


Fig. 4 Sensory evaluation of ASMP

Conclusion

This study has shown that apricot seed press cake (APC) can be effectively utilized to develop protein-rich, plant-based milk (ASM) and milk powder (ASMP) products. APC contained 49.75% protein, supporting its potential as a plant-based protein source. The formulated ASM contained 8.33% protein, 2.95% fat, and 12.04% total solids, while ASMP achieved 38.45% protein content and a low water activity (0.154), suggesting its potential for extended shelf life. Sensory analysis indicated moderate acceptability for ASMP (overall score >4.0/9), though ASM's low brightness ($L^* = 5.14$) may influence visual perception negatively. In terms of volatiles, benzaldehyde was the predominant volatile in ASM (79.15 µg/100 mL), but its level dropped markedly in ASMP (4.11 µg/kg) following spray drying, highlighting the need for improved processing to preserve key sensory compounds. Additionally, the high hygroscopicity (16.96%) and extended wettability time (332 s) of ASMP suggest that further optimization is required to improve physical stability and reconstitution behavior. Despite promising results, several limitations should be acknowledged. The sensory evaluation was conducted with a small semi-trained panel ($n = 10$), which may not fully reflect consumer preferences.

Only one apricot variety (Hacıhaliloğlu) was examined, which limits the generalizability of the results; i.e. other seeds of different apricot varieties should be examined due to differences in chemical composition. In addition, the health effects and bioavailability of the products were not evaluated and require future studies. In conclusion, apricot seed-derived products are promising as sustainable and functional ingredients for the development of plant-based foods. However, further research focusing on aroma retention, sensory improvements, and broader consumer validation is essential to increase their market potential.

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Author contributions TGD: Responsible for the design of the study, conceptualization, methodology development, data curation, formal analysis, writing the original draft, editing, and statistical analysis. AAH: Contributed to writing the original draft.All authors have read and approved the final version of the manuscript.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

Informed consent was obtained from all sensory evaluation panelists prior to their participation in the study. The study protocol was approved by the Inonu University Ethics Committee (approval number: protocol code 7074). All participants were informed about the study's purpose, procedures, and their right to withdraw at any time without any consequences. Informed consent was obtained from all sensory evaluation panelists prior to their participation in the study. The study protocol was reviewed and deemed exempt from formal ethics approval by the Institutional Review Board of Inonu University, as it involved only sensory evaluation with no direct impact on participants' health or well-being.

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