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Exploring the potential of fruit pomaces as sustainable food ingredients: a techno-functional approach

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A R T I C L E I N F O

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A B S T R A C T

Fruit processing generates large amounts of by-products such as pomaces, which are rich in dietary fiber and bioactive compounds but remain underutilized. Their techno-functional properties, which determine their performance in food matrices, have rarely been characterized in pomaces used in their as-received industrial form, limiting their valorization. This study evaluated the physicochemical and techno-functional properties of apple, orange, and grape wine pomace flours obtained directly from industrial processing and assessed the effect of particle size reduction through milling (1, 0.5, and 0.25 mm mesh sizes). The pomace type had a stronger influence on techno-functional properties than the degree of milling, mainly due to compositional differences among raw materials. Apple pomace flour exhibited the highest hygroscopicity (24.2%), solubility (61.6%), bulk density, and the best flowability (Carr's index 7.6%), suggesting suitability for dry mixes and instant formulations. Orange pomace flour showed high water retention capacity (5.0 g/g), swelling capacity, and low least gelation concentration (13.9%), indicating strong hydration and structuring potential. In contrast, grape wine pomace flour presented the highest content of insoluble fiber (lignin 42.7 g/100g) and water retention capacity (up to 6 g/g) but poor flowability and low solubility (11.6%), reflecting a predominantly structural behavior in food matrices. Increasing the degree of milling generally reduced particle size and flowability and, in some cases, increased hygroscopicity, which may influence powder stability during storage. These results provide relevant information for selecting suitable applications of fruit pomace flours and support the valorization of agro-industrial by-products as sustainable food ingredients.

1. Introduction

Fruits and vegetables constitute primary raw materials for the food processing industry. However, their transformation, particularly for juice or oil extraction, generates substantial amounts of by-products known as pomace or marc, which consist of the solid residues of skins, seeds, pulp, and stems remaining after pressing. These materials represent a significant economic and environmental challenge for both industry and society (Gowman et al., 2019). Among the most abundant of these residues are apple, grape, and orange pomaces, which are generated in big volumes by the juice and winemaking industries and constitute the focus of the present work.

Apple pomace (AP) is produced as a by-product, representing approximately 25% of the mass of processed fruit. It is composed of 95% skins, 2–4% seeds, and 1% stems, and was initially considered waste from the agri-food industry (Lyu et al., 2020). Many valorization pathways for AP have been reported, including biofuels (Vaez et al., 2023), compost (Ampese et al., 2023), applications in the food and beverages industry (Antonic et al., 2020; Curutchet et al., 2021), nutraceutical applications (Vandorou et al., 2024), and textile and other biomaterials (Gustavsson et al., 2011).

Winemaking generates large quantities of by-products, corresponding to about 30% w/w of the initial grapes. Grape pomace (GP) is composed of skins, pulp and seeds. The chemical composition of grape pomace is characterized by its high concentration of phenolic compounds (phenolic acids, flavonoids, tannins and stilbenes), dietary fiber, proteins, and minerals (Troilo et al., 2022).

During commercial orange juice production, large amounts of orange

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pomace (OP) are generated, which is composed of pulp, seeds, and peels that account for about 50% of the total weight of citrus fruits (de Castro et al., 2020). OP is rich in polyphenols, citric acid, dietary fiber, and pectin. Its major polyphenols such as hesperidin, naringin, and neohesperidin exhibit potent metabolic health benefits, making OP a promising option for nutraceutical applications across the food, cosmetic, and pharmaceutical industries (Srivastava et al., 2025).

For all these by-products, their traditional treatment as waste reflects not only an environmental liability but also a missed opportunity to use valuable resources. When inadequately managed, these residues contribute to the emission of greenhouse gases, the leaching of organic matter into soils and waterways, and the intensification of the ecological footprint of the food industry (Ahmad et al., 2024). Despite their rich composition in bioactive compounds, fibers, and functional compounds, fruit and vegetable pomaces remain underutilized in most industrial settings. This discrepancy highlights a critical gap between the growing global demand for sustainable raw materials and the persistent linearity of agri-food production models. Recent reviews have shown evidence on the health-promoting potential of fruit pomaces and their valorization into a circular-economy framework (Aguiar Pascoalino et al., 2025; Raczkowska & Serek, 2024).

Using these by-products in food products helps reduce waste and supports more sustainable and circular production practices. To develop the potential of fruit pomaces as sustainable food ingredients, it is essential to understand not only their nutritional value but also their techno-functional properties, which determine their behavior and performance within food matrices.

A growing effort in research has begun to characterize the techno-functional behavior of fruit and vegetable by-products and to relate it to their performance in real food matrices. Arcia et al. (2024) evaluated the effect of particle size on the bioaccessibility of phenolic compounds and the antioxidant capacity of orange, apple, and grape pomaces obtained from industrial processes. Although the work did not focus on techno-functional properties, the results underscore how structural and compositional differences, such as fiber and lignin content, affect the behavior of these ingredients. O'Shea et al. (2015) assessed apple and orange pomaces as functional ingredients and reported marked differences in their physicochemical and hydration-related properties, while Bas-Bellver et al. (2023) showed that the physicochemical, technological, and functional properties of upcycled vegetable waste ingredients are strongly influenced by processing conditions,

Zhang et al. (2025) evaluated the effects of physical modifications on kiwifruit pomace fibers and found that all treatments improved key techno-functional properties. Kauser et al. (2024) reported on the incorporation of AP into a wide variety of food products, including breads, cookies, cakes, muffins, yogurt, sausages, meat patties, jams, and chocolate spreads, where it has been shown to enhance fiber content, antioxidant capacity, emulsion stability, and textural attributes. However, despite documenting these diverse applications, the review does not specifically assess the techno-functional properties of apple pomace, which are critical for understanding its behavior in food matrices and for guiding its effective use in product development. Martínez-Martí et al. (2023) evaluated the impact of four treatments (hot air drying, freeze drying, homogenization, and extrusion) on the structure and techno-functional properties of clementine pomace powders. Their results demonstrate that these treatments significantly influence key functional attributes such as water and oil holding capacities, swelling capacity, solubility, and emulsifying capacity. Beyond the type of by-product, processing operations particularly milling and the resulting particle size have emerged as key levers to tailor these properties. Troilo et al. (2022) showed that the particle size of grape pomace flour modulates the nutritional, textural, and sensory quality of fortified muffins, Liu et al. (2016) found that the grinding method alters the structure and functional properties of insoluble dietary fiber from orange peel. Melios et al. (2025) point out that while numerous studies have explored the nutritional and bioactive composition of upcycled ingredients, there remains a significant gap in understanding how these by-products behave within food matrices, particularly from a techno-functional perspective. The techno-functional properties of fruit pomaces are currently the focus of growing research interest, as they play a central role in determining their performance in food applications.

It is well established that processing conditions can alter these properties. However, limited attention has been given to characterizing the techno-functional attributes of fruit pomaces as they are obtained directly from industrial processing. This study addresses this gap by evaluating the techno-functional properties of three fruit flours (apple, grape, and orange) obtained directly from industrial processing, assessing how particle size reduction through milling affects their functional performance, with the aim of better understanding their potential as sustainable food ingredients.

2. Materials and methods

2.1. Materials

The agro-industrial by-products employed in this study were derived from apple, orange, and grape processing. Fresh orange and apple pomace were acquired as by-products of industrial juice production in Montevideo, Uruguay, while Tannat grape pomace was obtained from a local winery in Canelones, Uruguay, following wine production.

2.2. Fruit pomace flour preparation

The apple, orange, and grape wine pomaces were placed on trays and dried in a convection oven (Alfa Laval Iberia SA, Spain) until the moisture content was lower than 12% (w/w), to achieve microbiological stability ($a_w < 0,65$). Once the dried pomaces reached room temperature ($\sim 25°C$), they were ground using a ZM200 Retsch ultra centrifugal mill (Retsch GmbH, Germany) using a 1 mm mesh size. One-third of the total amount of dried pomace ground at 1 mm size was retained while the remaining material was subsequently ground using a 0.5 mm mesh sieve. Then, half of the 0.5 mm ground sample was retained, and the remaining half was further ground using a 0.25 mm mesh sieve. At the end of this procedure, three flours with different particle sizes (1, 0.5 and 0.25 mm) were obtained for each fruit pomace (apple, orange and grape).

2.3. Physicochemical properties

2.3.1. Proximate composition

Grape, orange, and apple pomaces used in this study were previously analyzed for proximate composition (Arcia et al., 2024). Extractives, cellulose, hemicellulose, and lignin contents in the samples were determined according to the technical reports from the National Renewable Energy Laboratory (Sluiter et al., 2008; Sluiter et al., 2012). The protocols involve a two-step solvent extraction (water and ethanol) to remove soluble material, then a two-step sulfuric acid hydrolysis, and subsequent gravimetric and chromatographic analyses.

2.3.2. Water activity

Water activity (a_w) of the pomace flours was determined at 25°C using an Aqualab 47EV (Decagon Devices Inc., CA, USA) calibrated with standard solutions of $a_w = 0.253 \pm 0.003$ and $a_w = 0.506 \pm 0.003$.

2.3.3. Particle size distribution

Particle size distribution of the pomace flours was determined by laser light diffraction using an Anton Paar PSA 1190 L/D (Graz, Austria) in dry mode. For the analysis of the orange and apple pomace flours, an air pressure of 2 bar and a vibrator frequency of 30 Hz were selected, while for the grape wine pomace flour, the air pressure and the vibrator frequency were set at 1 bar and 20 Hz, respectively. These operating conditions were adjusted according to differences in the flowability of the samples and selected to obtain an obscuration of 0.5-1% with a vibrator duty cycle of 50%.

The D_{10}, D_{50}, and D_{90} percentiles were calculated based on the Fraunhofer reconstruction mode using the Kalliope software (version 2.34.3, Anton Paar).

2.4. Flowing properties

2.4.1. Poured and compacted bulk density

For the determination of the poured and compacted bulk density of the flours, a TA.XT Plus Texture Analyser equipped with a Powder Flow Analyser (Stable Micro Systems, UK) with a 49.0 N capacity was used. The results were obtained using Exponent software (Version 6.1.27.0, Stable Micro Systems).

Before starting the measurements, the force and height were calibrated, and the blade was centralized. A split vessel (internal diameter: 50 mm, total height: 100 mm, split height: 50 mm) was filled with the flour sample until 1 cm above the split division line. Then, a rotating helical blade (diameter: 48 mm and height: 10 mm) was used to apply two pre-conditioning cycles, in which the rotor moved down through the powder column at a tip speed of 50 mm/s and an angle of 175°, and then back up at 50 mm/s and 178°, to prevent differences in handling and filling from influencing the results. Then, the vessel was split, and the excess powder was removed, ensuring consistent sample volumes, which were weighed to calculate the poured bulk density (Eq. 1).

To determine the compacted bulk density, a flat compression probe (diameter: 47 mm) compressed the powder column at 1 mm/s until a force of 49.0 N was reached, then remained at the same distance for 120 s, before unloading at 0.5 mm/s. The compacted density was calculated according to Eq. 2.

$$Poured\ density = \frac{Sample\ weight\ (g)}{Volume\ of\ conditioned\ sample\ (mL)} \quad (1)$$

$$Compacted\ density = \frac{Sample\ weight\ (g)}{Volume\ of\ compressed\ sample\ (mL)} \quad (2)$$

2.4.2. Carr's index

Carr's index, also referred to as compressibility, was calculated according to Eq. 3.

$$Carr's\ index(\%) = \frac{Compacted\ density - Poured\ density}{Compacted\ density} \times 100 \quad (3)$$

The flowability of the pomace flours was classified according to their Carr's index as shown in Table 1.

2.4.3. Angle of repose (AoR)

The AoR of the flours was determined as described by Saha et al. (2023). Briefly, the powder samples were allowed to flow through a funnel positioned 20 mm above a flat surface, forming a conical heap. The diameter of the heap base was measured, and the AoR calculated as $\tan^{-1}$ of the relationship from the heap height (20 mm) and the base radius. At least five replicates were performed for each sample. The flowability of the pomace flours was classified according to their angle of repose as shown in Table 1.

Table 1
Powder flow classification by Carr's index and angle of repose (Juarez-Enriquez et al., 2022).

Flow classification	Carr's index (%)	Angle of repose (°C)
Excellent	< 15	< 30
Good	15 – 18	
Poor	18 – 22	30 – 45
Bad	22 – 35	45 -55
Very bad	35 – 40	> 55
Non-flowing	> 40	

2.5. Water-interaction techno-functional properties

2.5.1. Hygroscopicity

Hygroscopicity was evaluated in duplicate following the method reported by Sun-Waterhouse & Waterhouse (2015). Briefly, 1 g of sample was accurately weighed (W_i) and uniformly spread on plastic dishes, which were placed in a tight desiccator containing a saturated solution of NaCl (relative humidity of 75.5 %) and stored at 25°C. After seven days, the dishes were weighed (W_f) and the hygroscopicity was calculated according to Eq. 4.

$$Hygroscopicity\ (g\ H_2O\,/\,g\ powder) = \frac{W_f - W_i}{W_i} \quad (4)$$

2.5.2. Wettability

Wettability was defined as the time (in seconds) required for 3 g of pomace flour to penetrate the free surface of water at rest, as reported by Schuck et al. (2012).

2.5.3. Solubility index

The solubility index was determined in duplicate according to the method proposed by Bhat et al. (2023) with some modifications. Briefly, 1 g of sample was dispersed in 40 mL distilled water, vortexed for 2 min, heated at 85 °C for 30 min in a water bath, and centrifuged (6-16KS centrifuge, Sigma, Osterode, Germany), at 2200 × g for 15 min. An aliquot of the supernatant was dried at 102 °C to constant weight to determine the soluble solids content. The solubility index was calculated according to Eq. 5.

$$Solubility\ index\ (\%) = \frac{STS}{TS} \times 100 \quad (5)$$

Where STS represent the soluble total solids of the sample (g/100 g), and TS represent the TS (g/100 g) of the sample.

2.5.4. Swelling capacity

Swelling capacity was determined as the volume occupied by 2.5 g of pomace flour after mixing with 40 mL of water and leaving it to rest overnight (Ktenioudaki et al., 2013).

2.5.5. Water retention capacity

The water retention capacity (WRC) was determined according to Wang et al. (2015) with some modifications. Briefly, 2 g (W) of pomace flour was vigorously mixed with 20 mL of water for 30 s and allowed to stand at room temperature for 24 h. The mixture was then centrifuged at 4200 rpm for 10 min in a 6-16KS centrifuge (Sigma, Osterode, Germany), and the sediment was weighed (W_1) after removing the supernatant. The WRC was calculated as:

$$WRC\ (g\,/\,g) = \frac{W_1 - W}{W} \quad (6)$$

2.5.6. Least gelation concentration

Pomace flour suspensions in water of 12, 14, 16, 18, 20, 22, 24 and 26% were heated in a water bath at 87.5°C for 1 h and cooled down in an ice bath for 1 h. The LGC was determined as the minimum suspension concentration at which the sample did not slide down the tube when it was inverted (Wang et al., 2015).

2.6. Statistical analysis

The analyses were carried out in triplicate unless otherwise stated. Analyses of variance (ANOVA) were performed to determine significant differences (α = 0.05) among samples for a given pomace fruit or flour particle size. Post-hoc Tukey tests were performed at a confidence level of 95%. All statistical analyses were performed using InfoStat software (version 2020).

3. Results and discussion

3.1. Physicochemical properties

3.1.1. Composition

According to Arcia et al. (2024), the three flours show a high dietary fiber content, with grape pomace presenting the highest value (63.9 g/100g db) compared with apple and orange pomaces (33.8 and 23.1 g/100g db respectively). To gain a better understanding of possible differences in fiber compositions—which may subsequently explain variations in structure-associated properties—the content of cellulose, lignin, and hemicellulose was determined (Table 2).

As expected, the grape pomace had a higher amount of lignin compared with the apple and orange pomaces and, conversely, a lower amount of extractives in water. The high lignin content in the grape pomace can be explained by the nature of the original raw by-product, as a greater presence of stems and branches is typically found in grape pomace than in the other two fruit pomaces. According to Castro Sousa et al. (2014), agro-industrial grape residues mainly consist of solid by-products such as stalks, whereas apple pomace is occasionally composed of stems (Gowman et al., 2019).

In the case of the extractives, another distinctive aspect of the composition of the grape wine pomace compared with the other two by-products is that it had almost the same amount of extractives in water and extractives in ethanol, as well as and significantly more ethanol extractives. The high amount of extractives in ethanol may be explained by the higher presence of lipophilic compounds, as observed in the higher lipid content, quantified at 11.1 g/100g db (Arcia et al., 2024) and by other polyphenols that are less hydrophilic (e.g., tannins and flavonoids).

With respect to extractives in water, in the case of fruit pomaces, these include high amounts of pectin and non-structural compounds. Pectins are structural carbohydrates but, due to their high solubility, they behave as extractives and are removed in the aqueous extract fraction along with the non-structural compounds. In the case of orange and apple pomaces, the higher amount of extractives in water may be mainly related to the higher presence of pectin in these materials. Pectin values have been reported to range between 13% and 16.4% (Granucci et al., 2023; Szymanska-Chargot et al., 2017; Vaez et al., 2023) for apple pomaces, while values around 16% have been reported for oranges (Granucci et al., 2023).

Non-structural compounds may include non-structural sugars (mainly monosaccharides and disaccharides), inorganic material (soluble ash), nitrogenous material (e.g., soluble protein), and nitrates/nitrites (water-soluble inorganic material). Apples are known for their high concentration of monosaccharides. Fructose is typically the most abundant sugar in most varieties, followed closely by glucose. Sucrose is also present but generally in smaller proportions in ripe apples. Therefore, the predominant extracted sugars are fructose and glucose.

Table 2
Fiber characterization of the different pomaces.

Pomace flour	Extractives in water (g/100g)	Extractives in ethanol (g/100 g)	Cellulose (g/100 g)	Lignin (g/100g)	Hemicelluloses (g/100g)
Orange	44.94 ± 4.15 a	4.91 ± 1.31 a	9.86 ± 0.59 a	6.65 ± 0.11 a	5.39 ± 0.44 a
Apple	46.75 ± 0.46 a	2.55 ± 1.04 a	11.42 ± 0.43 a	13.94 ± 1.43 b	6.09 ± 0.24 a
Grape wine	14.77 ± 0.01 b	12.86 ± 0.12 b	6.17 ± 0.19 b	42.71 ± 0.32 c	7.62 ± 0.25 b

Expressed on a dry basis. Mean ± standard deviation. Different lowercase letters indicate significant differences ($p < 0.05$) among biomass types for each chemical component.

Oranges also contain these simple sugars. Glucose and fructose are the main components in the aqueous extracts, often followed by sucrose, which can be present in significant proportions. The large amounts of fructose and glucose present in these fruits contribute substantially to the high total carbohydrate concentration. Carbohydrate contents were higher in orange and apple pomaces (55.7 and 70.4 g/100 g db, respectively) compared with grape pomace (11.1 g/100 g db) (Arcia et al., 2024).

Among the orange and apple pomaces, it should be noted that the apple pomace had almost twice the lignin content of orange pomace. The lignin content could be directly related to the structural rigidity observed in some of the other analyses performed, such as the particle size distribution, as will be discussed later. The results obtained were similar to those reported in other studies (Castro Sousa et al., 2014; Gowman et al., 2019; Vaez et al., 2023; Yu & Ahmedna, 2013).

3.1.2. Moisture content and water activity

Although each pomace was dried to a safe moisture content (less than 12.1%), when the dry material was progressively milled (from 1 mm down to 0.5 mm and finally to 0.25 mm), the resulting fractions showed differences in moisture content upon analysis. These observed variations in moisture content directly affected their water activity (Fig. 1).

The water activity (a_w) of orange, apple, and grape wine pomaces ranged from 0.43 to 0.53, 0.21 to 0.23, and 0.49 to 0.29, respectively (Fig. 1.A). These values indicate that almost all water present in the apple pomaces corresponds to strongly bound water, present in the monolayer and unavailable to plasticize or participate in biochemical reactions. On the other hand, orange and grape pomaces present moderately bound water. Besides the lower moisture content of the apple pomace, this lower water activity may be explained also by the higher presence of carbohydrates in the apple pomace, particularly pectin, which is extracted in water. These water-soluble carbohydrates with free hydroxyl groups may contribute to a higher amount of bound water and, consequently, lower water activity (Mikus & Galus, 2025; Naqash et al., 2021).

On the other hand, despite having very different compositions, the water activities of orange and grape wine pomaces (milled at 1.0 mm) were similar. The explanation for this behavior could have different origins, considering the higher moisture content of the orange pomace. The relatively high a_w activity of orange pomace might be related to the lower pectin content and higher content of hydrophobic compounds, which is consistent with the almost twofold higher content of ethanol extractives in orange pomace compared to apple pomace (Martínez-Navarrete et al., 2023). A similar behavior may explain the case of grape pomace, where the higher presence of hydrophobic compounds, along with a significantly higher content of lignin and lignocellulosic matrix, results in increased a_w (Manich et al., 2021). Nevertheless, other aspects such as the degree of crystallinity of cellulose or the different types of lignin present in the pomaces could also affect a_w (Pejic et al., 2008).

Regarding the effect of particle size, a_w decreased in both orange and grape pomace as particle size was reduced, with the impact being greater in the case of grape pomace. Apple pomace showed almost the same a_w (or a slight increase) as particle size decreased. The effect of milling may mainly affect the lipophilic and lignocellulosic matrix, disrupting these structures and exposing hydroxyl groups, which in turn may interact with more water, thus decreasing a_w. On the other hand, as particle size decreases, the specific surface area (surface area per unit mass) of a material increases. A larger specific surface area means more sites are available for water interaction, which can influence the amount of bound water (water strongly attached to food components via hydrogen, ionic, or other bonds), as more hydroxyl or polar groups are exposed to interact with the water (Barbosa-Cánovas et al., 2007). The lower content of lipophilic compounds in the apple pomace would explain the almost constant water activity.

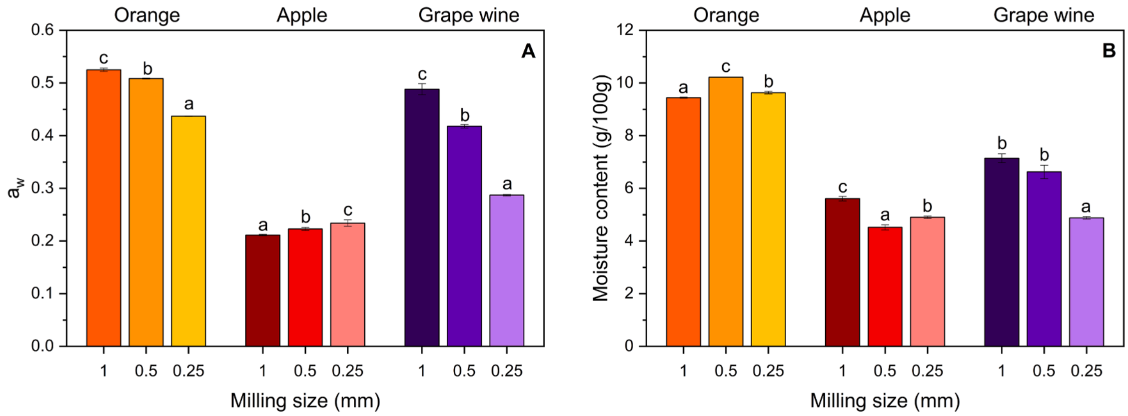

Fig. 1. a_w (A) and moisture content (B) of the of the orange, apple and grape wine pomace flours with different degrees of milling. Different lowercase letters within flour types indicate significant differences ($p < 0.05$) among milling sizes.

3.1.3. Particle size distribution

Before analyzing the particle size distribution of the pomace samples, it is relevant to mention the milling process used in this work because the results may be related to the equipment used for milling. The ZM 200 ultra-centrifugal mill is commonly used for rapid size reduction. The mill operates with a high-speed rotor that subjects the sample to both impact and shear stresses, pushing particles against a ring sieve until they are fine enough to pass through its holes. This principle allows the production of powders with controlled particle size distributions. The particle size distribution obtained with this type of mill depends on the anisotropic structure and composition of the plant fibers, highlighting that cellulose, lignin, and fibrillar organization determine how the material fractures and defibrillates during milling (Mayer-Laigle et al., 2020).

Fig. 2 shows the particle size distribution of fruit pomace flours, and Table 3 presents the D_{10}, D_{50}, and D_{90} percentiles.

Although the pomaces were subjected to the same milling procedure, using the same mesh sizes, the particle size distributions varied among pomace types. In the case of apple pomace, the flours milled using 1 mm and 0.5 mm mesh sizes, showed very similar particle sizes, with almost overlapping distributions (Fig. 2) and no significant differences ($P > 0.05$) in the D_{10}, D_{50}, and D_{90} values (Table 3). The fact that the particle size distribution of the 1 mm flour did not change after the subsequent milling using a smaller mesh size (0.5 mm) could be explained by a highly friable structure that, during the first milling round, reduced the particle size of the flour below 0.5 mm. Therefore, when the flour was submitted to a new milling procedure, it flowed directly through the 0.5-mm mesh without further size reduction. Apple pomace has a high content of carbohydrates (70.4 g/100 g db according to Arcia et al. (2024)), which in nature are less rigid than insoluble fibers such as cellulose and lignin. Therefore, during the initial milling, they can be broken down, while other components, especially lignin, require more force to fracture their structure. Additionally, as reported by Liu et al. (2016), milling can cause a redistribution of fiber components.

Table 3
Particle size distribution parameters (D_{10}, D_{50} and D_{90}) of the orange, apple and grape wine pomace flours with different degrees of milling.

Pomace flour	Milling size	D_{10} (μm)	D_{50} (μm)	D_{90} (μm)
Orange	1 mm	13.4 ± 0.1 bA	56.0 ± 0.1 cA	206.4 ± 0.5 cA
	0.5 mm	11.5 ± 0.2 bA	48.0 ± 1.9 bA	152.8 ± 20.6 bA
	0.25 mm	6.1 ± 1.4 aA	31.0 ± 0.9 aA	84.6 ± 2.5 aA
Apple	1 mm	21.8 ± 0.1 bB	73.6 ± 1.0 bB	274.1 ± 3.7 bB
	0.5 mm	21.1 ± 0.4 bB	73.8 ± 0.9 bB	274.2 ± 5.2 bB
	0.25 mm	13.2 ± 0.5 aB	44.4 ± 0.3 aB	101.0 ± 0.0 aB
Grape wine	1 mm	34.2 ± 0.2 cC	121.0 ± 0.3 cC	374.9 ± 0.6 cC
	0.5 mm	27.4 ± 0.5 bC	84.1 ± 0.2 bC	317.4 ± 2.1 bB
	0.25 mm	15.7 ± 0.2 aB	45.6 ± 0.4 aB	136.5 ± 1.2 aC

Mean ± standard deviation. Different lowercase letters within flour types indicate significant differences ($p < 0.05$) among milling sizes. Different uppercase letters within particle sizes indicate significant differences ($p < 0.05$) among flour types.

In the case of orange pomace, although the shape of the 1 mm and 0.5 mm flours distribution was also similar, significant differences ($P < 0.05$) were found for the D_{50} and D_{90} values, mainly explained by the reduction of a large size population (250 – 400 μm) observed in the 1 mm flour. Additionally, orange pomace contains less rigid fiber structures and, in particular, about half the lignin content of apple flour (Table 2).

The grape pomace 1 mm and 0.5 mm flours showed a clear bimodal distribution, with mean diameters of 80-90 μm and 300-400 μm. However, the volume of particles in the larger-size population decreased significantly after milling with the 0.5-mm mesh, explaining the

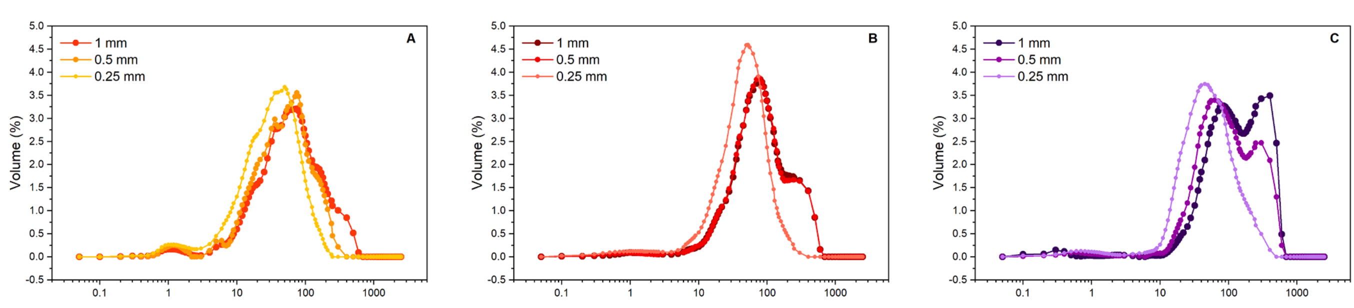

Fig. 2. Particle size distribution of the orange (A), apple (B) and grape wine (C) pomace flours with different degree of milling.

significant particle size reduction ($P < 0.05$). This may occur due to the composition of the pomace, as observed by Pietraccini et al. (2021): different compounds such as seeds, pulp and skins, exhibit different resistance to milling, which results in these two populations. After the third milling round using a 0.25-mm mesh size, all the flours presented noticeable changes in the shape of the particle the size distributions (Fig. 2). The changes observed include the complete disappearance of the shoulders corresponding to a population of particles with larger diameters, the shift of the main peak towards smaller diameters, and the reduction of the peak width, indicating lower heterogeneity in particle size. Moreover, D10, D50, and D90 showed a significant reduction ($P < 0.05$) for all three flours (Table 3).

The orange pomace flour presented the smallest particle size for the three flour sizes (1, 0.5, and 0.25 mm), followed by the apple and grape pomace flours. The only exception was observed for the 0.25 mm flours, where D10 and D50 values did not differ significantly ($P > 0.05$) between apple and grape pomace flours. The differences in the particle size may be explained by the resistance of rigid components such as lignin to milling. Fruit pomaces with higher lignin concentrations tend to produce larger particle sizes after milling (de la Rosa et al., 2010).

3.2. Flowing properties

The bulk density and flowing properties of the pomace flours are presented in Table 4. Bulk density is calculated as the ratio between the mass and volume of the powder under aerated conditions, i.e. including both the interstitial air and the pores within the particles (Juarez-Enriquez et al., 2022). Therefore, bulk density depends not only on the particle or true density, but also on the way particles pack together, which in turn is influenced by factors such as particle size distribution and particle shape (Schuck et al., 2012). Higher bulk densities are advantageous in terms of packing, storage and transport costs, whereas low bulk densities are often associated with particle agglomeration, negatively affecting powder flowability (Decker et al., 2024).

Apple pomace flours presented the highest bulk density values for each degree of milling ($P < 0.05$), while the effect of milling size varied among the different flours. The higher bulk density observed for apple flours cannot be directly explained by differences in particle size distribution and may therefore be related to differences in true density, defined as the density of the solid material excluding air (Schuck et al., 2012), and/or to particle shape. No clear overall trend was observed regarding the effect of milling size on bulk density, as this effect depended on the type of pomace flour.

The flowing properties of the flours were classified based on Carr's index (i.e. compressibility) and the angle of repose. Overall, Carr's index proved to be more sensitive, as it allowed the detection of a greater number of differences among flour types and particle sizes. In general, apple pomace flour exhibited the best flowability, as indicated by the lowest Carr's index and angle of repose values, whereas grape pomace flour showed the poorest flowability, and orange pomace flour displayed an intermediate behavior. Furthermore, although almost no significant differences in angle of repose were observed among milling sizes within each pomace type, Carr's index indicated a decrease in flowability with decreasing particle size (i.e. increasing degree of milling) for apple and grape wine pomace flours. In contrast, no clear trend was observed for orange pomace flour, whose flowability was classified as "good" for all three milling sizes.

Powder flowability is affected by several factors, including particle size and shape, density, moisture content, and composition (Juarez-Enriquez et al., 2022). The deterioration in flowing properties observed for apple and grape wine pomace flours as milling size decreased can be attributed to particle size effects. As particle size decreases, the specific surface area increases, strengthening cohesive forces and consequently impairing powder flowability (Suhag et al., 2024). On the other hand, grape wine pomace flours exhibited the largest particle sizes together with the poorest flowing properties (Tables 3 and 4). Therefore, the differences observed in flow behavior among flour types are likely governed more by compositional and surface characteristics than by particle size alone.

Apple pomace flours consistently showed the lowest moisture content and water activity (Fig. 1), which may have contributed to their enhanced flowability. In general, increasing moisture content promotes the formation of liquid bridges and capillary forces between powder particles, leading to reduced flowability (Juarez-Enriquez et al., 2022; Kim et al., 2005). Moreover, although grape pomace flours exhibited lower moisture contents than orange pomace flours, their flowability was poorer. This behavior may be associated with the oil content of grape pomace, which, when present at the particle surface, can impair flowability by forming liquid bridges between particles (Fitzpatrick, 2005; Suhag et al., 2024).

3.3. Water-interaction techno-functional properties

The pomace type significantly ($P < 0.05$) affected the hygroscopicity of the flours (Table 5). Apple pomace flour exhibited the highest hygroscopicity, followed by orange pomace flour, whereas grape wine pomace flours showed the lowest values. Hygroscopicity relates to the ability to absorb water from the environment, thus influencing stickiness and caking during storage and potentially limiting product stability and packaging options (Bas-Bellver et al., 2023). According to Schuck et al. (2012), apple pomace flour can be classified as a "very hygroscopic powder," orange pomace flour as a "slightly hygroscopic powder," and grape wine pomace flour as a "non-hygroscopic powder". The same trend was observed for water solubility. Both behaviors can be attributed to differences in flour composition. Apple pomace flour contains the highest concentration of carbohydrates with high water affinity, whereas grape pomace flours have the lowest concentration (Table 2). In addition, grape pomace contains the highest levels of hydrophobic components, such as fat and lignin.

The effect of particle size on hygroscopicity was less evident than the

Table 4
Bulk density, Carr's index and angle of repose (AoR) of the orange, apple and grape wine pomace flours with different degrees of milling.

Pomace flour	Milling size	Bulk density (g/mL)	Carr's index		Angle of repose	
			Carr's index	Classification	AoR (°)	Classification
Orange	1 mm	0.37 ± 0.00 aA	15.9 ± 0.1 aB	Good	29.3 ± 0.7 aB	Excellent
	0.5 mm	0.43 ± 0.03 aA	16.5 ± 0.0 bB	Good	29.3 ± 1.7 aB	Excellent
	0.25 mm	0.42 ± 0.01 aB	15.9 ± 0.0 aA	Good	31.5 ± 1.4 aB	Poor
Apple	1 mm	0.56 ± 0.01 bC	7.6 ± 0.5 aA	Excellent	26.1 ± 1.9 aA	Excellent
	0.5 mm	0.52 ± 0.01 bB	11.9 ± 1.0 bA	Excellent	26.2 ± 1.3 aA	Excellent
	0.25 mm	0.47 ± 0.01 aC	16.6 ± 1.2 cA	Good	25.2 ± 0.2 aA	Excellent
Grape wine	1 mm	0.45 ± 0.01 cB	21.3 ± 0.3 aC	Poor	31.9 ± 0.8 aC	Poor
	0.5 mm	0.39 ± 0.01 bA	33.5 ± 0.6 bC	Bad	31.8 ± 1.6 aB	Poor
	0.25 mm	0.35 ± 0.00 aA	37.5 ± 0.8 cB	Very bad	33.7 ± 1.7 aC	Poor

Mean ± standard deviation. Different lowercase letters within flour types indicate significant differences ($p < 0.05$) among milling sizes. Different uppercase letters within particle sizes indicate significant differences ($p < 0.05$) among flour types.

Table 5
Water-interaction techno-functional properties of the orange, apple and grape wine pomace flours with different degrees of milling.

Pomace	Milling size	Hygroscopicity (%, w/w)	Wettability (s)	WRC (g/g)	Swelling capacity (mL/g)	LGC (%, w/w)	Solubility index (%, w/w)
Orange	1 mm	11.4 ± 0.1 aB	26 ± 1	5.0 ± 0.1 bB	7.8 ± 0.3 aB	13.9 ± 0.1 aA	32.8 ± 5.5 aB
	0.5 mm	12.0 ± 0.1 bB	74 ± 8	5.3 ± 0.2 bC	7.9 ± 0.0 aB	15.9 ± 0.4 bA	27.4 ± 1.7 aB
	0.25 mm	13.8 ± 0.0 cB	> 120	4.4 ± 0.2 aC	8.3 ± 0.1 aB	16.2 ± 0.2 b	31.7 ± 0.1 aB
Apple	1 mm	24.2 ± 0.2 cC	> 120	2.0 ± 0.1 aA	7.2 ± 1.2 aB	14.0 ± 0.2 aA	61.6 ± 2.4 aC
	0.5 mm	23.8 ± 0.1 bC	> 120	1.9 ± 0.1 aA	8.5 ± 0.5 aB	16.2 ± 0.2 bA	61.0 ± 0.4 aC
	0.25 mm	23.4 ± 0.1 aC	> 120	2.0 ± 0.1 aA	9.1 ± 0.1 aB	16.1 ± 0.4 b	60.8 ± 0.3 aC
Grape	1 mm	3.4 ± 0.1 aA	> 120	6.0 ± 0.4 bC	3.2 ± 0.0 aA	23.0 ± 1.4 B	11.6 ± 0.3 aA
	0.5 mm	3.6 ± 0.2 aA	> 120	3.8 ± 0.5 aB	3.6 ± 0.3 aA	22.3 ± 0.1 B	10.3 ± 0.5 aA
	0.25 mm	5.6 ± 0.0 bA	> 120	3.9 ± 0.2 aB	4.8 ± 0.0 bA	> 26	13.4 ± 0.1 bA

WRC: water retention capacity; LGC: least gelation concentration. Different lowercase letters within flour types indicate significant differences ($p < 0.05$) among milling sizes. Different uppercase letters within particle sizes indicate significant differences ($p < 0.05$) among flour types.

effect exerted by pomace type, although an increase in hygroscopicity was found as the particle size of orange and grape pomaces decreased, particularly as flours were milled to 0.25 mm, consistent with previous studies (Calabuig-Jiménez et al., 2018; Khushbu et al., 2020). As particle size decreases, the surface area increases, enhancing water transport from the surrounding air to the solid particles (Khushbu et al., 2020). This trend was not observed for apple pomace flour, where the highest hygroscopicity was obtained for the 1 mm flour, followed by 0.5 mm and 0.25 mm particle sizes. Nonetheless, the least hygroscopic apple pomace was still more hygroscopic than any orange and grape pomace, emphasizing the dominant effect of composition.

In contrast, almost no effect of particle size was observed on solubility. The solubility index was determined by stirring the flours in water under heating conditions, whereas hygroscopicity was measured by allowing the flours to stand. This methodological difference likely explains the less pronounced influence of particle size on solubility.

Wetting is considered the first stage of powder rehydration, in which the particles come into contact with the surrounding liquid, leading eventually to the sinking of the particles, their disaggregation of particle agglomerates and, finally, their solubilization (Fitzpatrick et al., 2016). Therefore, longer wetting times indicate lower wettability. Wettability is usually enhanced by increasing particle diameter, which reduces the surface-to-volume ratio, by increasing powder density, which favors particle sinking, and by reducing the concentration of hydrophobic components at the particle surface, among other factors (Rodríguez Arzuaga et al., 2021). All flours were classified as non-wettable (wettability > 120 s) independently of the degree of milling, except for orange pomace flour, which showed an increase in wetting time as particle size decreased (Table 5). This trend may be explained by the increase in surface area, which increases the time required to fully wet the particle surface, as well as by enhanced particle–particle interactions that may promote agglomeration (Camacho et al., 2022). The better wettability obtained for orange pomaces milled using 1-mm and 0.5-mm mesh sizes cannot be explained by a larger particle size, higher density, or bulk composition of the flours. Therefore, it may be related to the surface hydrophilicity of the particles, which is not always consistent with their bulk composition.

In the present work, WRC was calculated as the amount of water retained by the material after being subjected to an external force, i.e. centrifugation. The different fruit pomaces presented significantly different WRC, with apple pomace presenting the lowest values (~ 2 g/g), while orange and grape pomaces ranged from 3.8 to 6.0 g/g (Table 5). The WRC of orange pomace flours may be explained by the high pectin content of citrus fruit (Jongaroontaprangsee et al., 2007). In the case of grape pomace, the higher WRC compared to apple pomace may be associated with the higher content of insoluble dietary fiber and lignocellulosic components, particularly lignin and cellulose, which contribute to the formation of a porous structure capable of retaining larger amounts of water within the fiber matrix (Castro et al., 2025; Dey et al., 2021). An effect of particle size was observed on the WRC of orange and grape wine pomaces, particularly when comparing 1 mm and 0.25 mm degrees of milling. WRC, which represents the ability of a matrix to entrap water under the application of a gravitational force, depends on the fiber dimension, and can be impaired by the damage to the fiber structure caused by grinding (Luca et al., 2022).

Grape wine pomace flours exhibited the lowest swelling capacity and required the highest concentration to form a gel (≥ 22%), whereas apple and orange pomace flours showed higher swelling capacities and lower least gelation concentrations (LGC), ranging from 14% to 16% (Table 5). No significant differences ($P > 0.05$) were observed between apple and orange pomace flours for swelling capacity. The higher swelling and lower LGC observed in apple and orange pomaces may be associated with a matrix that is more readily hydrated and capable of forming a continuous network upon heating, while the composition of grape pomace may hinder effective network development, thus requiring higher concentrations to achieve gelation. These results could be explained by a synergistic effect of the high pectin content combined with the low starch concentration present in orange and apple pomaces (O`Shea et al., 2015; Roman-Benn et al., 2023; Spinei & Oroian, 2021).

Practical application

The techno-functional characterization of fruit pomace flours provides valuable information for their potential use as functional ingredients in food formulations. The three pomaces evaluated in this study exhibited markedly different properties, suggesting complementary application opportunities depending on the desired functionality.

Apple pomace stands out as a source of soluble fiber with high hygroscopicity, high solubility, and excellent flowability. Its relatively low water retention capacity indicates that it contributes mainly to soluble fiber enrichment rather than to structural or textural development. These characteristics make apple pomace particularly suitable for applications requiring rapid hydration and smooth dispersion, such as instant beverages, powdered mixes, or dry nutritional premixes. In addition, its good bulk density, low water activity, and favorable flow properties facilitate dosing, transport, and industrial handling. The results also indicate that particle size reduction mainly affects powder handling properties, such as bulk density and flowability, while having limited impact on hydration-related functionality.

Orange pomace exhibited high water retention capacity, high swelling capacity, and a low least gelation concentration, indicating a strong ability to interact with water and contribute to structure formation. These characteristics suggest potential applications as a structuring and hydrating fiber in products where moisture retention is relevant, such as baked goods, reformulated dough systems, meat products, or plant-based analogues. Orange pomace flour maintained good flowability across the evaluated particle sizes, facilitating its incorporation into dry ingredient systems. In this case, particle size reduction mainly affected water-interaction properties, including hygroscopicity, wettability, water retention capacity, and gelation behavior, suggesting that milling can be used to modulate hydration-related functionality.

Grape wine pomace is characterized by its high content of insoluble fiber, low hygroscopicity, high water retention capacity, and low solubility. These properties indicate that it behaves primarily as a structural ingredient capable of providing body and mechanical strength in solid food matrices. Consequently, it may be suitable for applications such as crackers, baked snacks or high-fiber extruded products, as well as meat-based or plant-based analogues where reinforcement of the product matrix is desirable. However, the relatively poor flowability of grape pomace flour, which becomes more pronounced with decreasing particle size, may limit its use in process requiring precise dosing or pneumatic transport. In this case, milling mainly intensified powder handling limitations rather than significantly improving hydration-related functionality.

4. Conclusions

Fruit pomace flours obtained from industrial processing exhibited markedly different techno-functional properties, mainly determined by pomace type and composition rather than by degree of milling. Apple pomace flour showed the highest solubility, hygroscopicity, bulk density, and the best flowability, suggesting suitability for powder instant formulations. Orange pomace flour exhibited strong hydration-related functionality, including high swelling capacity and low gelation concentration, indicating high potential for hydration and moisture retention applications. In contrast, grape wine pomace flour was characterized by high insoluble fiber content and water retention capacity, but poor flowability and low solubility, reflecting predominantly structural behavior in food matrices.

Particle size reduction generally decreased flowability and, in some cases, increased hygroscopicity, which may affect powder stability during storage by promoting caking. These results highlight the importance of considering both composition and particle size when selecting fruit pomace flours for specific food applications and processing conditions. Overall, the findings support the valorization of fruit processing by-products as sustainable functional food ingredients.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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