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Upcycling strawberry pomace into functional cookies: Dietary fiber enrichment, antioxidant delivery, and bioaccessibility after simulated digestion

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ABSTRACT

Strawberry pomace, an underutilized residue from juice processing, provides abundant dietary fiber and polyphenols, which may contribute to health promotion. The objective of this study was to valorize this residue by producing strawberry pomace flour (SPF) through freeze-drying and milling, and incorporating it into cookies as a functional ingredient. SPF was characterized for its fiber content, total phenolic content (TPC), and antioxidant capacity (ABTS). For cookies development, wheat flour was partially replaced with SPF (15 and 30%), and cookies were evaluated for composition, technological properties (color, texture, and geometrical parameters), TPC, and antioxidant activity during in vitro gastrointestinal digestion. SPF exhibited high levels of fiber (43.1 ± 0.4 g/100 g), TPC ($3{,}100 \pm 100$ mg GAE/100 g), and antioxidant

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activity (9,900 ± 100 mg TE/100 g). Enriched cookies showed approximately twofold and fourfold increases in dietary fiber at 15 and 30% substitution, respectively, compared to the control cookie. A 30 g serving of cookies with 30% substitution provided 12% of the recommended daily intake of fiber. Polyphenol content and antioxidant activity were also enhanced, with values approximately doubled at the highest substitution level, and remained bioaccessible after digestion. Technological quality was maintained, supporting SPF as a sustainable resource to enhance the nutritional profile of cookies.

KEYWORDS

upcycled ingredients, functional foods, polyphenol bioaccessibility, strawberry pomace

1. INTRODUCTION

Nearly 50% of the output from the fruit processing industry is comprised of by-products, primarily consisting of exocarp, seeds, and pomace, resulting from the extraction of juice and the discarding of damaged or immature raw materials (Raczkowska and Serek, 2024).

The valorization of these plant-derived by-products has recently emerged as a key strategy in the agri-food sector to enhance sustainability and reduce environmental impact (Rolewicz et al., 2025). Residues from fruit processing are increasingly recognized as valuable sources of bioactive compounds, including dietary fiber, antioxidants, and various phytochemicals, making them suitable alternatives for upcycling into functional food ingredients (Berenguer et al., 2023).

Strawberries rank as a major fruit crop in the agro-industrial sector, with global production exceeding 8 million tons per year (Villamil-Galindo et al., 2021). Strawberries are highly perishable and tend to deteriorate more rapidly than many other fruits due to their high postharvest respiration rate. Consequently, large quantities of agricultural waste are generated as strawberries that fail to meet quality standards are discarded. Moreover, strawberry pomace is commonly treated as waste following juice extraction processes (Ong and Nyam, 2022). In recent years, strawberry pomace has been identified as a promising material rich in bioactive and functional constituents. This residue is particularly rich in dietary fiber and contains relevant amounts of proteins and polyphenols. Additionally, its polysaccharide profile comprises pectin, xyloglucan, xylan, β-glucan, and glucomannan, as well as free sugars such as glucose, fructose, and arabinose. Such components emphasize the suitability of strawberry pomace to be used as a functional food ingredient that can improve the nutritional profile and bioactive content of reformulated food products (Hotchkiss et al., 2024; Petrov Ivanković et al., 2024; Pukalskienė et al., 2021).

The incorporation of fruit by-products into food formulations can lead to a range of physical, chemical, and nutritional modifications in the resulting product. These outcomes are influenced by multiple factors, including the specific type of by-product applied, the processing methods it undergoes, and the overall composition of the enriched food matrix (Hasan et al., 2024). Cookies represent one of the most suitable alternatives for incorporating such functional ingredients, since they are widely consumed as snack products due to their extended shelf life, ease of storage, and broad range of varieties. Their ready-to-eat nature contributes to their popularity across all age groups. However, conventional cookie formulations typically consist of refined flour, sugar, and butter, resulting in products that are energy-dense but limited in dietary fiber and health-promoting bioactive compounds (Krajewska and Dziki, 2023).

Despite the nutritional and bioactive profile of the strawberry pomace, it remains largely underutilized in food applications. While various fruit pomaces have been successfully tested in cookie formulations, such as apple (Kruczek et al., 2023; Naseem et al., 2024), grape (Fontana et al., 2024), pomegranate (Muhammad et al., 2023), bilberry, and blackcurrant pomaces (Shoukat et al., 2025; Nour et al., 2025), among others, the application of strawberry pomace in these products remains scarcely explored. Tarasevičienė et al. (2021) formulated cookies with up to 20% strawberry pomace flour and reported sensory acceptability and an increase in phenolic compounds.

Although reformulating cookies with upcycled ingredients can contribute to healthier and more sustainable diets, it is crucial to ensure that such modifications do not negatively impact the technological quality. Changes in formulation, such as the inclusion of non-conventional flours, increased fiber content, modified fat type or quantity, or reduced levels of added sugars or salt, can impact key attributes, including appearance, texture, and geometrical parameters. These factors determine the overall technological performance of the final product (Lingiardi et al., 2023).

In light of the above, this work aimed to obtain and characterize strawberry pomace flour (SPF), and to evaluate its partial incorporation into cookies by assessing their composition, technological properties, and the release of polyphenols during in vitro gastrointestinal digestion. It is worth noting that while the enrichment of baked products with fruit-derived by-products has been widely explored in terms of total polyphenol content, only a few studies have assessed the extent to which these compounds remain bioaccessible after digestion. However, to the best of our knowledge, no studies have examined the digestibility of polyphenols from strawberry pomace incorporated into cookie matrices. This represents a critical knowledge gap, as the health benefits of polyphenols rely not only on their presence in the food matrix but on their bioaccessibility. Without this insight, estimations of nutritional and functional value remain incomplete. By integrating in vitro gastrointestinal digestion assays, this study provides a relevant assessment of the functional potential of strawberry pomace-enriched cookies, offering novel evidence that bridges food reformulation and nutritional bioavailability.

2. MATERIALS AND METHODS

2.1. Materials

Wheat flour type 000 (Molino Juan Semino S.A., Argentina), refined sugar (David Rosental e Hijos S.A.I.C., Argentina), high-oleic sunflower oil (Cañuelas, Argentina), instant oats (Morixe, Argentina), baking powder (Kraft Foods, Argentina), potable water, and fresh mature strawberries (San Andreas cv.) purchased from a local market. Folin–Ciocalteu reagent, 6-hydroxy-2,5,7,8-tetramethylchroman-2-carboxylic acid (Trolox), 2,2′-azino-bis 3-ethylbenzthiazoline-6-sulphonic (ABTS) acid, α-amylase (A-3176, from porcine pancreas), pepsin (P-7000, from porcine gastric mucosa), pancreatin (P-1750, from porcine pancreas), and bile (B-8631, porcine extract) were purchased from Sigma-Aldrich. All other reagents were of analytical grade.

2.2. Strawberry pomace flour production

Strawberry juice was prepared using a centrifugal juicer (Yelmo, Argentina) from fresh strawberries that were previously washed. The strawberry pomace was the residue retained in the filter of juice. This residue was freeze-dried (Liotop, USA) at −53 °C and 38 μmHg, and then milled using a laboratory colloid mill (<240 μm) (Tecnodalvo, Argentina) to obtain strawberry pomace flour (SPF). The SPF was stored at 4 °C until analysis.

2.3. Strawberry pomace flour characterization

2.3.1. Dietary fiber content. Soluble dietary fiber, insoluble dietary fiber, and total dietary fiber (TDF) contents were quantified following AOAC method 991.43 (AOAC, 2000). Briefly, approximately 1 g of defatted, dry sample was weighed and subjected sequentially to enzymatic digestion with heat-stable α-amylase, protease, and amyloglucosidase. Insoluble fiber was separated by filtration, washed, dried, and corrected for residual protein and ash contents. Soluble fiber was precipitated from the filtrate using ethanol, collected by filtration, dried, and similarly corrected. IDF and SDF contents were calculated and adjusted for sample moisture and fat, and TDF was obtained as the sum of IDF and SDF. All analyses were conducted in triplicate.

2.3.2. Chemical extracts obtention. For the assessment of total phenolic content (TPC) and antioxidant activity of the SPF, chemical extracts were obtained in duplicate following the procedure described by Liao et al. (2021) with slight modifications. Briefly, for the first extraction, exactly 1.0 g of SPF was weighed, and 10 mL of a methanol: HCl (pH 2) mixture (50:50) was added. The mixture was stirred for 1 h, and then centrifuged (Giuminelli, Argentina) at 3,500 rpm for 15 min. The supernatant was separated, and a second extraction was performed on the residue using 10 mL of an acetone: water (70:30) mixture following the same procedure. Finally, both supernatants were pooled.

2.3.3. Total polyphenol content. The TPC was assessed using the Folin–Ciocalteu assay, according to the procedure described by Llopart et al. (2023) with slight adjustments. Briefly, 40 μL of the sample, 2 mL of Folin–Ciocalteu reagent (diluted 1:10 with distilled water), and 1 mL of 7.5% Na_2CO_3 were mixed. After a 10-min incubation period at 40 °C, the absorbance was measured at 760 nm using a UV/Vis spectrophotometer (Metrolab 330, Argentina). Measurements were compared against a standard curve of gallic acid over a concentration range of 0.025–0.7 mg mL^{-1}. Results were expressed as mg of gallic acid equivalents per 100 g of sample (mg GAE/100 g). The assay was performed in triplicate.

2.3.4. Antioxidant activity. The ABTS radical cation ($ABTS\bullet^{+}$) decolorization assay was conducted according to the method described by Re et al. (1999) with slight modifications. $ABTS\bullet^{+}$ was obtained by reacting a 7 mM ABTS solution with 2.45 mM potassium persulfate and incubating it in the dark at room temperature for 16 h. Once the $ABTS\bullet^{+}$ radical was formed, it was diluted with an ethanol:water mixture (50:50) until reaching an absorbance value of 0.70 ± 0.02 at 730 nm. For the analysis, 60 μL of each sample was combined with 840 μL of the $ABTS\bullet^{+}$ solution and incubated in the dark for 25 min before measuring the absorbance at 730 nm using a UV-VIS spectrophotometer (Metrolab 330, Argentina). To express the results, a calibration curve was obtained using Trolox at a concentration range between

0.1 and 0.01 mg mL^{-1}. Results were expressed as antioxidant activity in mg of Trolox equivalents per 100 g of sample (mg TE/100 g). All analyses were performed in triplicate.

2.4. Cookie formulation

Control cookies (CC) were prepared using wheat flour, sugar, water, high-oleic sunflower oil, oats, and baking powder. Two additional formulations were obtained by partially replacing wheat flour with 15% or 30% SPF, hereafter referred to as SPFC-15 and SPFC-30, respectively (Table 1). For dough development, sugar, previously hydrated oats, and sunflower oil were mixed until a creamy consistency was achieved. The remaining dry ingredients, previously sifted, were gradually incorporated, adding water as needed to obtain a homogeneous dough. The dough was then rolled out and cut into circular shapes using a cutter. Cookies were baked in a preheated electric convection oven (Met Zonda S.A., Argentina) at 180 °C for 8 min and then allowed to cool to room temperature before analysis.

2.4.1. Cookie characterization

2.4.1.1. Chemical composition. Chemical composition of cookies was determined: moisture (AOAC 984.25), ash (AOAC 900.02), protein (AOAC 979.09), fat (920.85), soluble, insoluble, and total dietary fiber (AOAC 991.43), and carbohydrates (estimated by difference) (AOAC, 2000). The fatty acid profile was also assayed by gas chromatography–mass spectrometry (Agilent, USA) according to ISO 12966-2, 2017. The results were expressed based on the degree of unsaturation of the fatty acids of the sample. All analyses were performed in triplicate.

2.4.1.2. Technological characterization: color, geometrical, and textural parameters. The color parameters L^* (lightness), a^* (red-green component), b^* (yellow-blue component), and the browning index (BI) were determined from digital images of the cookie surfaces acquired with a digital camera (EOS Rebel T3, Canon, Thailand), following the method described by Rossi et al. (2020). Cookie size parameters, such as diameter and thickness, were assessed with a measuring tape and a caliper (Ruhlmann, China), according to the procedure reported by Jadhav et al. (2021). The spread ratio was calculated according to Abdel-Moemin (2015) as the ratio between the mean diameter and the mean thickness. Texture analysis was performed using a three-point bending test on a Multitest 2.5-d motorized testing machine (Mecmesin Ltd., UK) fitted with a

Table 1. Ingredients of control cookie (CC) and cookies with 15 and 30% SPF replacement (SPFC-15 and SPFC-30)

Ingredients (%)	CC	SPFC-15	SPFC-30
Wheat flour	47	38	30
SPF	0	7	13
Sugar	21	20	20
Oil	13	13	13
Oat	3	3	3
Water	15	18	20
Baking powder	1	1	1
Total	100	100	100

SPF: strawberry pomace flour.

100 N load cell. The test was conducted at a crosshead speed of 180 mm min^{-1}, applying force until the cookie fracture occurred. Hardness was expressed as the maximum deformation force (N) required to fracture the cookie. All technological analyses were performed in five replicates ($n = 5$).

2.4.2. In vitro gastrointestinal digestion of cookies. The in vitro digestion of the cookie formulations (CC, SPFC-15, and SPFC-30) was performed according to the standardized INFOGEST 2.0 protocol (Minekus et al., 2014), which involves sequential phases of salivary, gastric, and intestinal digestion. Simulated digestive fluids (salivary, gastric, and intestinal fluids, 1.25×; i.e., 25% more concentrated than the final fluids to compensate for the dilution occurring when enzymes and other components are added) were prepared from stock saline solutions and adjusted to pH 7.0, 3.0, and 7.0, respectively, using 6 M HCl. Enzyme solutions (amylase, lipase, pepsin, and pancreatin) and bile salts were freshly prepared before use. For each phase, specific volumes of enzymes and salts were added to 5 g of the cookie samples, followed by incubation with agitation at 37 °C (2 min for the oral phase and 120 min for both gastric and intestinal phases). pH adjustments were made with HCl or NaOH as required. After digestion, samples were centrifuged, and aliquots of the solubilized fraction were collected and stored at −20 °C for further analysis. Enzyme blanks (without sample) were also prepared in duplicate.

2.4.2.1. Total phenolic content and antioxidant activity of cookies in chemical extracts and digested samples. The TPC and antioxidant activity were evaluated in chemical extracts obtained from the cookie formulations (CC, SPFC-15, and SPFC-30) according to the procedure described in Section 2.3.2, as well as in aliquots of the solubilized fractions from the in vitro digestion, following the methods for TPC and antioxidant activity determination detailed in Sections 2.3.3 and 2.3.4.

2.5. Statistical analysis

Statistical analyses were conducted using SigmaStat 3.5 software (SYSTAT Software, Inc.). Results are presented as mean ± standard deviation of replicates. Experimental data were analyzed by analysis of variance (ANOVA), followed by Tukey's post-hoc test for multiple comparisons, with a significance level of 0.05.

3. RESULTS AND DISCUSSION

3.1. Strawberry pomace flour characterization

Table 2 summarizes the characterization results of the SPF. The average total dietary fiber (TDF) content was higher than values reported in the literature for strawberry pomace (33.9%), where the raw material used was a blend of the Sonata, Rumba, and Darselect varieties, produced in Latvia (Górnaś et al., 2016). However, other authors reported a TDF content of 60.0% for strawberry pomace obtained from an industrial facility producing concentrated strawberry juice, in which a blend of varieties commonly cultivated for industrial processing in Poland (Sega Sengana, Polka, Honeoye, Kama, and Dukat) was used (Sójka et al., 2013). Recently, Hotchkiss et al. (2024) reported a TDF content of approximately 55%, which is about 1.3 times higher than the value obtained in our study. In their work, insoluble fiber accounted for nearly 90% of the

Table 2. Fiber content, total phenolic content, and antioxidant activity of strawberry pomace flour extracts

Total dietary fiber (%)	43.1 ± 0.4
Soluble dietary fiber (%)	10.0 ± 0.3
Insoluble dietary fiber (%)	33.1 ± 0.1
Total phenolic content (mg GAE/100 g)	3,100 ± 100
Antioxidant activity (mg TE/100 g)	9,900 ± 100

Data are presented as mean values and standard deviations from three samples ($n = 3$).

total. In contrast, in our sample, the insoluble fraction accounted for roughly 75% of the TDF, with the presence of strawberry achenes contributing to this fraction. This indicates not only a greater overall fiber content in their pomace but also a higher proportion of the insoluble fraction compared to our findings. These differences underscore the significant impact of strawberry variety and genotype, as well as cultivation conditions, on the composition of the resulting pomace. Additionally, variations in the processing methods applied in the different studies mentioned above could represent another important factor affecting the composition of the retained pomace fraction (Pukalskienė et al., 2021).

The total phenolic content (TPC) and antioxidant activity of SPF extracts are shown in Table 2. The TPC was similar to the ranges reported for strawberry pomace and its extracts. Pukalskienė et al. (2021) reported extract TPC values of up to approximately 4,680 mg GAE/100 g, which varied according to both the solvent and the extraction technique. Other recent studies report lower pomace TPC ranges than our findings. A recent work reported TPC values of ≈530–1,340 mg GAE/100 g (dw) across different berry pomaces (including strawberry) and extraction protocols (Petrov Ivanković et al., 2024), while Villamil-Galindo et al. (2021) found cultivar-dependent TPC in strawberry by-products ranging from ∼610 to 1,500 mg GAE/100 g. It is essential to highlight that the high fiber content previously mentioned may facilitate fiber–polyphenol interactions, with bound phenolic compounds being either released or retained, depending on the processing or extraction method. Such matrix effects may explain the wide variability in polyphenol yields reported across different methodologies (Hotchkiss et al., 2024).

Given their key role in neutralizing and scavenging free radicals, phenolic compounds are closely linked to the antioxidant potential of the matrix. Therefore, variations in antioxidant activity are often associated with differences in TPC, which can also be influenced by the extraction method and solvent used (Koraqi et al., 2023). The antioxidant activity of the SPF extracts was similar to that reported by Tumbas Šaponjac et al. (2015), with values ranging from approximately 90–110 mg TE g^{-1} in strawberry pomace extracts, as measured by the ABTS assay. This activity was attributed to their high content of total flavonoids and anthocyanins, particularly protocatechuic acid, catechin, and pelargonidin-3-glucoside. More recently, Petrov Ivanković et al. (2024) investigated the antioxidant capacity of various berry pomaces, using the ABTS method. They reported that strawberry pomace exhibited an antioxidant activity of approximately 95 mg TE g^{-1} (dw), closely aligning with the value obtained in our study. Comparatively, raspberry and blueberry pomaces demonstrated higher ABTS antioxidant activities, ranging from 120 to 160 mg TE g^{-1} (dw), which may be related to differences in phenolic composition and concentration among these berries. However, Pukalskienė et al. (2021) reported considerably higher values (148.5–391.9 mg TE g^{-1} dw), also assayed by the

ABTS method, in optimized pressurized-liquid extracts of strawberry pomace; these differences are likely attributable to the use of stronger extraction conditions.

3.2. Cookie characterization

3.2.1. Chemical composition. The chemical composition of the formulated cookies is shown in Table 3. Cookie moisture was observed to increase with increasing SPF content in the recipe. This behavior can be related to the higher dietary fiber content introduced with the pomace, which enhances water retention capacity. This effect is mainly attributed to the hydroxyl groups present in the fiber structure, which enable stronger interactions with water molecules through hydrogen bonding (Huang et al., 2025). A comparable trend was reported in a previous research on wheat-flour cookies fortified with 5–15% apple pomace powder, which demonstrated that increasing levels of such pomace significantly enhance water absorption capacity, thereby increasing cookie moisture (Naseem et al., 2024). The ash content of the cookies also increased with the addition of SPF, which may be related to minerals naturally occurring in strawberries and further concentrated through the SPF production process (Bastias-Montes et al., 2023). For protein content, only slight changes were observed among the formulations, likely because the protein content is similar in both wheat flour and SPF. The replacement of 15 and 30% of wheat flour with SPF resulted in minor changes in total fat content, with the cookies reflecting the lipid profile of the fat source used in all formulations. Accordingly, a predominance of unsaturated over saturated fatty acids was noted. Among the unsaturated fatty acids, oleic acid was predominant, while no trans fatty acids were detected. As for carbohydrates, their levels decreased as SPF was incorporated into the formulation. The partial replacement of wheat flour in the formulations reduces starch content; however, the incorporation of SPF may contribute to sugar content, which may explain why the differences in carbohydrate content among the cookie formulations were not pronounced.

Table 3. Chemical composition of control cookie (CC) and cookies with 15 and 30% SPF replacement (SPFC-15 and SPFC-30)

	CC	SPFC-15	SPFC-30
Moisture (%)	8.8 ± 0.1^{c}	9.2 ± 0.1^{b}	11.0 ± 0.1^{a}
Ash (%)	0.8 ± 0.01^{b}	1.0 ± 0.1^{ab}	1.4 ± 0.1^{a}
Proteins (%)	5.9 ± 0.1^{a}	5.9 ± 0.1^{a}	5.7 ± 0.1^{b}
Total fat (%)	15.6 ± 0.2^{a}	15.4 ± 0.1^{a}	14.9 ± 0.1^{b}
Saturated fatty acids (%)	1.6 ± 0.1^{a}	1.6 ± 0.1^{a}	1.3 ± 0.1^{b}
Unsaturated fatty acids (%)	14.0 ± 0.2^{a}	13.8 ± 0.1^{a}	13.6 ± 0.1^{a}
Oleic acid (%)	11.8 ± 0.1^{a}	11.5 ± 0.1^{a}	11.8 ± 0.2^{a}
Trans fatty acids (%)	0	0	0
Total dietary fiber (%)	2.5 ± 0.3^{c}	4.2 ± 0.1^{b}	9.9 ± 0.2^{a}
Soluble dietary fiber (%)	0.20 ± 0.01^{c}	1.3 ± 0.1^{b}	3.5 ± 0.1^{a}
Insoluble dietary fiber (%)	2.3 ± 0.3^{c}	2.90 ± 0.01^{b}	6.4 ± 0.1^{a}
Carbohydrates (%)	66.4 ± 0.1^{a}	64.4 ± 0.3^{b}	57.3 ± 0.7^{c}
Sodium (mg/100 g sample)	212 ± 23^{a}	184 ± 10^{a}	188 ± 24^{a}

Data are presented as mean values and standard deviations from three samples ($n = 3$). Different letters indicate significant differences ($P < 0.05$) between samples.

For dietary fiber content, values for SPFC-15 and SPFC-30 showed approximately twofold and fourfold increases, respectively, compared to the CC. This increase corresponded to a marked rise in insoluble dietary fiber. The dietary fiber content of the cookies depends on the fiber contribution of the ingredients and their proportion in the formulation. Zlatanović et al. (2019) found a dietary fiber content of 10% in cookies prepared with apple pomace, which has a fiber content similar to that of the present study, using a comparable replacement level (25%). A similar trend was observed by Nour et al. (2025), who reported that partial replacement of wheat flour with bilberry and blackcurrant pomace powders (2.5–10%) significantly increased the fiber content of cookies. Similarly, Bastias-Montes et al. (2023) reported that incorporating 5–10% maqui flour, rich in fiber (33.4%) from its seeds and husks, led to a sixfold increase in the dietary fiber content of cookies. These results highlight that even small additions of fruit pomace can substantially enhance the fiber content of those baked products. In the present study, a 30 g serving (three units) of SPFC-30 provided 12% of the recommended daily intake of fiber, and consuming two servings (e.g., at breakfast and as an afternoon snack) would supply nearly 25% of the daily requirement (Institute of Medicine, 2005). According to the Codex Alimentarius, a product can be labeled as a “source of dietary fiber” when it provides at least 3 g/100 g, and as “high in dietary fiber” when it contains at least 6 g/100 g (Codex Alimentarius Commission, 2009). These criteria are consistent with those established by the European Regulation (EC - No 1924/2006) on nutrition and health claims. Thus, SPFC-30 reached 9.9 g/100 g of TDF, exceeding the threshold to be classified as “high in fiber”, while SPFC-15, providing 4.2 g/100 g, met the criteria to be considered a “source of fiber”, respectively.

3.2.2. Technological characterization. As shown in Fig. 1, the color parameters and visual appearance of the cookies varied with formulation. The L^* values declined as wheat flour was increasingly replaced with SPF. This darker coloration may be attributed to the higher reducing sugar content in SPF, which promotes Maillard and other browning reactions. This darkening effect has also been reported by Tarasevičienė et al. (2021) and Nour et al. (2025) in cookies formulated with different levels of wheat flour replacement by strawberry, bilberry, or blackcurrant pomaces, respectively. For the b^* parameter, only minor changes were observed: it remained similar between the CC and SPFC-15, whereas it slightly decreased in SPFC-30. However, the a^* parameter increased when wheat flour was partially replaced with SPF. These variations were expected considering the intrinsic color of SPF. Tarasevičienė et al. (2021) reported lower a^* values than those found in the present study for cookies formulated with up to 20% strawberry pomace flour. The difference observed may stem from variations in the color of pomace and to the fact that the authors used milk powder as an ingredient, which may alter the color of the dough and the final product.

Regarding the browning index, and in line with the observations for the L^* parameter, it showed a pronounced increase with higher SPF content in the cookie formulations. This may be related to Maillard reactions that occur during baking between reducing sugars and proteins, contributing to the brown color of the food (Qi et al., 2025). Consistent with our findings, recent studies have reported an increase in browning index when fruit pomaces are incorporated into cookie formulations. Cookies supplemented with dried sea buckthorn fruit and apple pomace showed a significantly higher browning index and darker color compared with controls, which has been attributed to intensified Maillard reactions and the formation of heat-induced

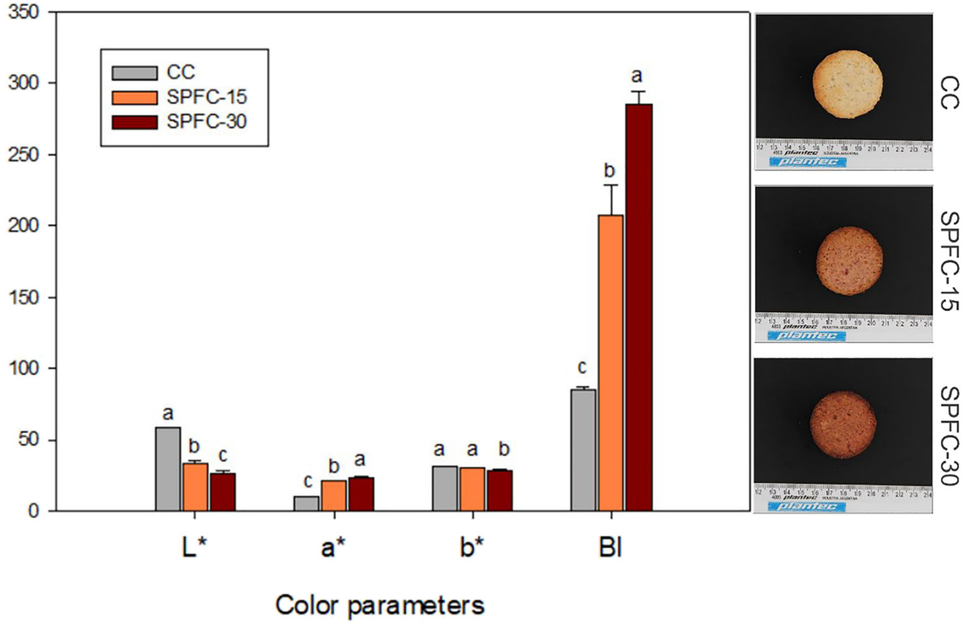

Fig. 1. Visual appearance and color parameters of control cookie (CC) and cookies with 15 and 30% strawberry pomace flour replacement (SPFC-15 and SPFC-30). Different letters indicate significant differences ($P < 0.05$) between samples. Own source/creation

compounds, such as 5-hydroxymethylfurfural and melanoidins, during baking (Karpińska-Tymoszczyk et al., 2024; Naseem et al., 2024).

The geometrical and textural parameters of the formulated cookies are presented in Table 4. Analysis of cookie dimensions revealed no significant differences in diameter, whereas thickness decreased significantly with increasing levels of wheat flour replacement by SPF. The decrease in thickness of SPF-enriched cookies may be associated with the dilution of gluten and the increase in fiber content of the wheat flour-SPF composite dough. In these formulations, the reduced

Table 4. Technological parameters of control cookie (CC) and cookies with 15 and 30% SPF replacement (SPFC-15 and SPFC-30)

	CC	SPFC-15	SPFC-30
Textural parameters			
Maximum force (N)	35 ± 3^a	31 ± 3^a	36 ± 3^a
Geometrical parameters			
Diameter (cm)	4.83 ± 0.03^a	4.77 ± 0.07^a	4.81 ± 0.04^a
Thickness (cm)	1.35 ± 0.02^a	1.10 ± 0.02^b	1.00 ± 0.02^c
Spread ratio	3.57 ± 0.04^c	4.33 ± 0.13^b	4.82 ± 0.03^a

Data are presented as mean values and standard deviations from five replicates ($n = 5$). Different letters indicate significant differences ($P < 0.05$) between samples.

gluten content, combined with increased fiber levels, may have hindered gluten network development and decreased dough viscosity, resulting in thinner baked cookies (Chikpah et al., 2023). The spread ratio increased with the addition of SPF, due to the reduction in thickness as the SPF content increased in the formulation. These observations are consistent with recent reports on cookies enriched with grapefruit and apple pomace powders, which evaluated the impact of their incorporation on the physicochemical properties of cookies (Kausar et al., 2024; Naseem et al., 2024). Other authors have reported variable results when incorporating different sources of dietary fiber into cookie formulations. The variability in results across studies may stem from differences in the chemical composition of raw materials and formulation parameters, since cookie dimensions during baking are strongly influenced by the degree of flour replacement, the water-holding capacity of ingredients, and the specific source of dietary fiber incorporated (Jose et al., 2022; Mancebo et al., 2018; Naknaen et al., 2016; Laguna et al., 2014).

The textural properties showed similar maximum force values between the CC, SPFC-15, and SPFC-30, despite the substantial increase in dietary fiber with SPF addition. Comparable results were reported by Laguna et al. (2014) in their study on the addition of apple fiber to a cookie formulation. This fiber exhibited an insoluble-to-soluble fiber ratio of 75/25, comparable to the ratio determined for the SPF used in the present work (67/32). This ratio is noteworthy, as Mancebo et al. (2018) demonstrated smaller variations in cookie texture when soluble fiber was incorporated and more pronounced changes with the addition of insoluble fibers. Insoluble fibers are generally associated with structural reinforcement, which would be expected to increase cookie hardness. Conversely, soluble fibers, due to their water-binding capacity, as evidenced by the higher moisture in SPFC-15 and SPFC-30, tend to mitigate this effect by reducing hardness (Martínez et al., 2014). Our results showed that these opposing contributions appeared to balance each other, resulting in cookie hardness values comparable to the CC. Moreover, residual sugars in SPF may also act as plasticizers within the dough matrix, mitigating the typical hardness increase observed in fiber-enriched cookies (van der Sman and Renzetti, 2019). Consequently, no significant change in cookie hardness was observed with SPF incorporation. This contrasts with previous reports in which the addition of fruit pomace or other fiber-rich by-products resulted in firmer textures. For instance, recent studies have shown that incorporating 15% grapefruit pomace significantly increased cookie hardness (Kausar et al., 2024). Formulations containing blueberry and blackcurrant pomace powders also exhibited increased dough hardness at inclusion levels above 5% (Nour et al., 2025).

3.2.3. Total phenolic content and antioxidant activity in chemical extracts and digested samples. Figure 2(A) shows the TPC of the samples, measured in both chemical extracts and enzymatic digests. In both cases, TPC increased as the substitution of wheat flour by SPF in the cookie formulation increased. These findings are in agreement with previous studies reporting increased phenolic content in cookies enriched with grape, apple, and hog plum pomaces (Antoniolli et al., 2024; Zlatanović et al., 2019; Oladunjoye et al., 2021). Moreover, in the SPF-containing formulations, no significant differences in TPC were observed between the two methods. This is probably because the measured polyphenols correspond to the extractable fraction. In line with the nutritional relevance of consuming extractable and non-extractable polyphenols, recent works have reviewed that the non-extractable antioxidants remaining after digestion will continue along the intestinal tract, being released and metabolized by the action of the microflora, thereby producing significant biological effects (Shahidi and Hossain, 2023; Nemzer et al., 2025).

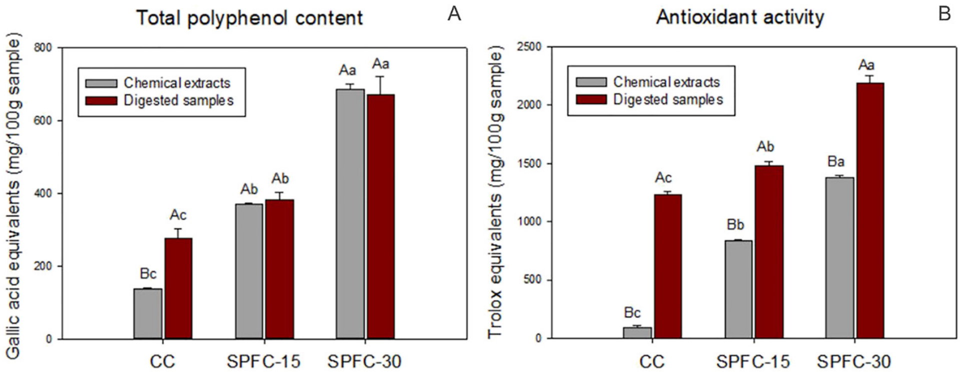

Fig. 2. Total phenolic content **(A)** and antioxidant activity **(B)** of chemical extracts and digested samples of control cookie (CC) and cookies with 15 and 30% SPF replacement (SPFC-15 and SPFC-30). Lowercase letters indicate significant differences ($P < 0.05$) between samples. Uppercase letters compare chemical extracts and digested samples. Own source/creation

Figure 2(B) shows the antioxidant activity of the samples, evaluated in both chemical extracts and enzymatic digests. In both cases, the results followed the same trend as observed for TPC, with an increase in the antioxidant activity of the cookies as the replacement level of wheat flour with SPF in the formulation increased. Unlike TPC, the enzymatic digests exhibited greater antioxidant activity than the chemical extracts across all cookie samples analyzed. Antioxidant compounds are not limited to polyphenols. They are grouped into categories such as carotenoids, phytosterols, alkaloids, terpenoids, tocotrienols, and organosulfur compounds, among others (Jideani et al., 2021). During the digestion of the samples, antioxidant compounds, non-polyphenols, may be released from the cookie matrix, which are not liberated in the case of chemical extracts. This may explain the difference observed when comparing the antioxidant activity determined by both methods.

Overall, our results indicate that at the highest replacement level, the TPC and antioxidant activity of the cookies were doubled. Although no official dietary reference exists for polyphenol intake, it has been estimated that individuals following a Mediterranean diet consume ~1,000 mg of gallic acid equivalents per day (Zamora-Ros et al., 2018). Based on this value, a 30 g serving (three cookies) of SPFC-30 would provide roughly 20% of this average intake, and consuming the cookies twice daily could contribute nearly 40% of the daily polyphenol intake. These results underscore the potential of SPF-enriched cookies as a functional food, delivering bioactive compounds with antioxidant properties and supporting polyphenol intake as part of a balanced Mediterranean-style diet.

4. CONCLUSION

This study highlights the potential of valorizing a by-product of strawberry juice production by reducing its moisture content, enabling milling and stabilization, and allowing its use as a functional food ingredient.

Strawberry pomace flour (SPF) was found to be a rich source of dietary fiber, exhibiting a higher fiber content comparable with other fruit-derived by-products reported in the literature. Cookies enriched with SPF (15 and 30%) showed a significant increase in dietary fiber, which may contribute to improving fiber intake among consumers. This functional enrichment did not compromise the technological quality of the cookies: although the thickness decreased with increasing levels of SPF, the diameter and hardness remained as the control, and the spread ratio increased moderately, reflecting the balance between ingredients in the dough.

Additionally, the inclusion of SPF increased both total phenolic content and antioxidant activity, suggesting that these cookies may serve as a dietary source of antioxidants with potential health-promoting properties. The in vitro digestion assay revealed that the release of polyphenols and antioxidant activity significantly increased in the digested fractions, highlighting the bioaccessibility of these compounds and reinforcing the nutritional value of SPF-enriched cookies.

Therefore, this work provides stronger evidence supporting the use of upcycled ingredients as an effective and innovative strategy for repurposing strawberry pomace into a value-enhancing component for the development of cookies with potential health benefits. These cookies may help address common dietary deficiencies by increasing daily intake of dietary fiber and antioxidants. Nonetheless, further research is needed to assess consumer acceptability and the commercial feasibility of incorporating such products into the food market, while also exploring more cost-effective dehydration alternatives to freeze-drying.

Declaration of competing interests: The authors declare that the work reported in this article was not influenced by competing financial interests or personal relationships.

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