






Grape pomace flour: A functional and sustainable ingredient for gluten-free pasta

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ABSTRACT

Grape pomace (GP), a winemaking by-product rich in polyphenols and anthocyanins, was used as a functional ingredient to enhance the nutritional and functional properties of gluten-free pasta. Grape pomace flour (GPF), from red grape varieties, was characterized for its moisture content (2.13 ± 0.41 g/100 g), total polyphenols (1773.52 ± 207.24 mg GAE/100 g), anthocyanins (72.38 ± 16.18 mg/100 g), pH (3.59 ± 0.02), titratable acidity (12.32 ± 0.45 g/100 g), fibre (64.1 ± 5.02 g/100 g), water binding capacity (420.38 ± 15.75 g/100 g), and oil binding capacity (340.63 ± 57.97 g/100 g). Gluten-free fettuccine was formulated with 0%, 5%, and 10% GPF, and the cooking, chemical, and physical properties of both fresh and dried pasta were evaluated. The incorporation of GPF significantly affected the pasta's functional properties and nutritional profile. The optimal cooking time increased from approximately 5 min for control samples (0% GPF) to about 7 min for pasta containing 10% GPF. Enriching gluten free pasta with GPF significantly increased the content of bioactive compounds. Total polyphenol content increased from three to sixfold compared to the control sample, depending on the level of GPF added and the drying process. Furthermore, anthocyanin content increased up to 88.05 ± 4.14 mg/kg in fresh gluten free pasta samples, however, the drying process induced degradation of these pigments up to 29%. The results showed that fortifying gluten-free pasta with grape pomace flour improves its nutritional and functional properties and promotes circular gastronomy practices through the valorisation of agri-food by-products and their sustainable reintroduction into the food system.

1. Introduction

Consumer perception of gluten-free products has evolved beyond medical necessity to include wellness-oriented lifestyle choices. Technological advances in gluten-free formulations are addressing traditional limitations in taste, texture and nutritional content through new ingredient applications and innovative processing techniques (Papageorgiou and Varzakas, 2023).

Pasta is a staple of Italian cuisine and the Mediterranean diet. It is widely appreciated for its taste, ease of preparation, and affordability. Global consumption has almost doubled over the past decade, to reach 17 million tons per year, with Italy's per capita consumption at 23 kg/year (Unione Italiana Food, 2024). Although pasta is nutritionally rich in complex carbohydrates, it also provides proteins, lipids, fibre, minerals, and vitamins (Zingale et al., 2023). However, both traditional and gluten-free pastas, are often poor in bioactive compounds. Celiac patients commonly show deficiencies in fibre, vitamins (B12, D), and minerals (calcium, iron, zinc, magnesium), antioxidant compounds and

gluten-free products often lack optimal texture, color, and flavor (Oniszczyk et al., 2019). In order to improve the nutritional value and sensory quality of pasta, formulations enriched with cereals, pseudo-cereals, legumes, and agro-industrial by-products have been studied including olive pomace, tomato peel, green banana, apple, carrot, mango, and grape pomace (Simonato et al., 2019; Betrouche et al., 2022). Agri-food by-products represent 30% of global food production but they are underused due to perishability and high disposal costs. EU regulations (EC Regulation 852/2004) mandate environmentally sound disposal, making valorisation a sustainable alternative aligned with Agenda 2030 goals for health and responsible production (Agenda 2030 for Sustainable Development, 2015). Recently Nyberg et al. (2022), defined the concept of circular gastronomy as “*The knowledge and skills of food and meal designs, focusing on re-creation and re-design, in order to stimulate gastronomic development for a sustainable future*”. This also involves converting by-products or waste into functional, value-added ingredients that improve nutritional quality and promote sustainability.

In Italy, the wine industry generates about 10 million tons of grape

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pomace (GP) yearly, a by-product consisting of skins, seeds, and stalks, recognized as a high-value functional ingredient for the food industry (Oliveira et al., 2022; Weis et al., 2025). GP is a source of bioactive compounds, including anthocyanins, flavan-3-ols, flavanols and stilbenes (Zmuncilă et al., 2026) with a great impact on human health, contributing to the prevention of chronic diseases (e.g., diabetes mellitus) (Neagu et al., 2024). Moreover, GP is also an exceptional source of dietary fibre (up to 65% of dry weight), mainly insoluble, able to form complexes with phenolic compounds, which are released into the intestine during digestion (Troilo et al., 2022). In food formulations, GP could be used as a “vehicle” for these nutrients, transforming traditional products into functional foods (Weis et al., 2025).

Studies have successfully incorporated GP into different matrices such as cheeses, yogurts, chocolates, and specifically cereal-based products like bread, muffins, and pasta (Barbaccia et al., 2022; Fernández-Fernández et al., 2022; Liberatore et al., 2025; Zmuncilă et al., 2026 and references therein). The use of GPF in pasta significantly increase total phenolic content and antioxidant capacity (Tolve et al., 2020; Bianchi et al., 2021; Gerardi et al., 2023; La Gatta et al., 2023).

The bioaccessibility and the bioavailability of phenolic compounds is influenced by several factors, such as chemical structure of phenolics, food matrix composition as well as host. The presence of fibre, carbohydrates, proteins or lipids may influence the bioaccessibility due to the interactions between food matrix and the bioactive compound; food processing may positively or negatively affect the bioaccessibility and bioavailability of polyphenols (Melini et al., 2020). Furthermore, the metabolism of phenolics in the gastrointestinal tract can produce bioactive metabolites (Melini et al., 2020). Hence, bioavailability is a compromise between the phenolic compounds lost during processing and those absorbed into the organism ().

Another nutritional advantage is the modulation of the starch digestibility: GP inclusion significantly lower the glycemic index by increasing slowly digestible starch and resistant starch while decreasing rapidly digestible starch (Liberatore et al., 2025).

However, the incorporation of grape pomace into starchy food matrices presents distinct technological challenges depending on the product type. As highlighted by recent systematic reviews (Boff et al., 2022; Weis et al., 2025), most applications are currently concentrated on baked goods, such as biscuits and cookies. Unlike baked goods, pasta undergoes to hydrothermal treatment (boiling), which present a critical challenge for gluten-free products enriched with fibres: maintaining structural integrity and preventing excessive bioactive compound leaching into the cooking water.

Recent studies have incorporated grape pomace into fresh pasta (Tolve et al., 2020; Bianchi et al., 2021; Oliveira et al., 2022; La Gatta et al., 2023; Liberatore et al., 2025) highlighting that GP particles act as a high-fibre particulate that disrupt the gluten network, producing a weaker dough. Fibre, moreover, interfere also with the starch-protein matrix, leading to the loss of gelatinized starch (Oliveira et al., 2022; Zmuncilă et al., 2026) even if the gluten network acts as a support, mitigating the structural weakening caused by the fibre (Iuga and Mironeasa, 2020a).

Gluten-free (GF) pasta is typically made using rice and corn, which have low nutritional value due to their high content of rapidly digestible starch (RDS) and poor technological properties (Marti and Pagani, 2013; Trevisan et al., 2019). Composite flours have been used to enhance the nutritional content of gluten-free pasta (Melini et al., 2020, and references therein). However, the use of GF pasta remains largely unexplored. The applications of GP in gluten free food formulation remain limited with previous studies focusing on muffins (Baldán et al., 2021) and on breadstick, biscuits and focaccia, where the addition up to 5% of GP improved the antioxidant capacity without compromising consumer acceptability (Cardone et al., 2025).

In this context, there is a lack of data on the use of grape pomace in gluten-free pasta formulations. This study therefore aims to evaluate the use of red grape pomace flour (GPF) obtained from the autochthonous

Etna varieties Nerello Mascalese and Nerello Cappuccio as a functional ingredient in gluten free pasta. For this purpose, two inclusion levels of GPF (5–10%) in the pasta formulation were assessed, and the impact on nutritional quality and technological properties was studied. Additionally, the influence of the pasta drying process on the physicochemical, nutritional, and functional properties of the fortified gluten-free pasta was investigated.

2. Materials and methods

2.1. Grape pomace flour

The grape pomace belonged to the Nerello Mascalese and Nerello Cappuccio cultivars was supplied by the Barone di Villagrande winery (Milo, Catania, Italy). After maceration and fermentation, the grape pomace (GP) was pressed, frozen and transferred to the Di3A laboratory. After pomace was thawed, dehydrated in a B-Dry 0616 dryer (Ariete, Firenze, Italy) at 55 °C for 24 h, as this method is cost-effective, accessible and easily replicable. Afterwards, the rasps and grape seeds were separated, and the skins ground into flour (grape pomace flour, GPF) using a home grinder (Tritapiù, Imetec, Azzano S. Paolo, Bergamo, Italy) and then sieved (ASTM mesh 35, 500 µm) to achieve a uniform particle size (Fig. 1). The obtained GPF was stored in an airtight, dark plastic container until analysed or used for pasta preparation (Tolve et al., 2020). GPF was characterised for moisture content, pH and total acidity, total polyphenol content, total anthocyanins content, fibre content, water binding capacity and oil binding capacity. All the analysis were performed in triplicate and data reported in tables were expressed as mean value ± standard deviation.

2.1.1. Grape pomace characterization

Moisture content (g/100 g) was determined by gravimetric method at 105 °C with a circulating air oven (ThermoScientific, Heratherm oven, MA, USA) until constant weight (Kutlu et al., 2026). Titratable acidity (TA) was determined by titration with 0.1 M NaOH until pH 8.1 was reached. 2 g of GPF was added with 30 mL of water and mixed for 40 min before pH measurement (Mettler Toledo MP 220 pH meter) and titration (AOAC 942.15 Method). Acidity was expressed as g of tartaric acid/100 g of GPF dry weight (DW). Total (TDF), soluble (SDF) and insoluble (IDF) dietary fibre was determined according to the enzymatic method AOAC 991.43 using the Total Dietary Fiber Assay Kit (K-TDFR, Megazyme, Ireland).

2.1.2. Extraction and determination of total polyphenol content (TPC)

Polyphenol extraction was carried out on 1 g of GPF using three



Fig. 1. Dried flour grape pomace.

aliquots of 5 mL methanol:water:acetic acid solution (80:19:1 v/v). The mixture was sonicated for 1 h (Ultrasonic cleaning instrument, FALC, Italy) and centrifuged (5478×g, 10 °C, 20 min) (Thermo Scientific SL16R, USA). The supernatant was collected and the extraction was repeated twice on the remaining pellet (Monteiro et al., 2021). The methanolic extracts were reunited and diluted to a ratio of 1:50 with distilled water before total polyphenols content determination. The polyphenols extraction was performed in triplicate. Total polyphenol content (TPC) was determined by the Folin-Ciocalteu method (Singleton et al., 1999), using gallic acid as a standard. 1 mL of diluted extract was mixed with 5 ml of 10% Folin's reagent and allowed to react for 5 min in the dark. Then 4 ml of 7.5% sodium carbonate (Na₂CO₃) were added, and the mixture was kept in the dark for 150 min. The absorbance was read at 765 nm against blank using a UV/VIS spectrophotometer (PerkinElmer Precisely, Lambda 25). A calibration curve ($y = 0.0942x - 0.0007$; $R^2 = 0.9999$) using gallic acid standards at different concentrations (1.05-10.5 mg/100 g) was prepared, and the results were expressed as milligrams of gallic acid equivalents (GAE) per 100 g of GPF DW.

2.1.3. Extraction and determination of total anthocyanin content (TAC)

Anthocyanin extraction was carried out following the method described by Monteiro et al. (2021). 25 mL of a methanol, water solution (1:1) acidified with 0.1% HCl were added to 2 g of GPF. The mixture was vortexed for 2 min, sonicated in an ultrasonic bath (Ultrasonic cleaning instrument, FALC, Italy) for 3 h, and centrifuged (5478×g, 10 °C, 20 min) (Thermo Scientific SL16R, USA). The supernatant was separated from the pellet and filtered with a syringe filter (0.45 μm, Albet). The extraction was performed in triplicate. Total Anthocyanin Content (TAC) was determined using the differential pH method according to AOAC 2005.02. Two identical aliquots of the extract were transferred into two different volumetric flasks and brought up to a volume: one with the buffer solutions at pH 1.0 (KCl and HCl), and the other with buffer solution at pH 4.5 (CH₃COONa and HCl), using a 1:10 dilution ratio. The blank was prepared with distilled water. A UV/Vis spectrophotometer (PerkinElmer, Lambda 25) was used to measure the absorbances of the solutions at 520 nm and 700 nm against the blank. TAC was calculated as follows and expressed on dry weight:

$$\text{TAC (mg/kg)} = A \times Mw \times FD \times 10^3 / \epsilon \times 1$$

A (absorbance) = (A_{520-A700}) pH1 - (A_{520-A700}) pH4.5.

FD = dilution factor.

Mw (molar mass) = 449.2 g/mol for cyanidin-3-glucoside

ε (molar extinction coefficient) = 26900 L × Mol⁻¹ × cm⁻¹

10³ = conversion factor from g to mg.

2.1.4. Determination of water and oil binding capacity (WBC, OBC)

Water Binding Capacity (WBC) and Oil Binding Capacity (OBC) were measured following the method of Kahraman et al. (2018) and the analysis was performed in triplicate. 2 g of GPF were mixed with 24 mL of water or seed oil in a Falcon tube, vortexed for 20 min, and then centrifuged 5478×g, 20 °C, 15 min) (Thermo Scientific SL16R, USA). After centrifugation, the pellet was separated from the supernatant and weighed. Binding capacity was calculated using the formula:

$$\text{WBC o OBC (\%)} = (\text{pellet weight} / \text{flour weight}) \times 100$$

2.2. Gluten-free pasta production

To produce gluten-free pasta a mix (Pasta Venezia, Rubano, Padova, Italy) containing corn starch, potato starch, rice flour, thickeners (guar gum) and salt was used. The nutritional composition of the mix was as follows: fat 0.4 g/100 g, of which saturated 0.3 g, carbohydrates 83.7 g/100 g, of which sugars 0.1 g, protein 2.21 g/100 g, salt 1.66 g.

Pasta was produced using the Girmi Pasta machine equipped with a Teflon die in fettuccine format, 25 cm × 0.2 cm x 1.0 cm (length x thickness x width). All samples were prepared using the same procedure: mixing water and flour, kneading for 6 min, extrusion, and cutting. Control fresh pasta (CTPF) was obtained by mixing the gluten free mix with water; pasta with GPF, was obtained replacing 5 % (V5PF) and 10 % (V10PF) of the mix with GPF. After an aliquot of each gluten free pasta sample was placed in a static oven at 55 °C for 24 h to obtain the dried pasta samples (CTPD; V5PD, V10PD). Each formulation was produced in double. Table 1 reports the composition of gluten free pasta samples and code.

2.2.1. Analysis of chemical and physical properties of gluten-free pasta

Moisture determination was carried out gravimetrically, using the same procedure described in paragraph 2.1.1. Acidity was determined as described in section 2.1.1. Extraction and analysis of total polyphenols were carried out using the procedure as previously described in section 2.1.2. TAC was determined using the procedure described in Section 2.1.3, varying the dilution ratio to 2:10 (sample: solvent). As concern fibre content, the values reported for fresh and dried pasta were theoretically determined, based on the fibre content of grape pomace.

Color parameters (L*, a*, b*) were measured using a Chroma Meter CR-400 (Minolta) colorimeter, on three different point of the surface of 10 fettuccine for each gluten-free pasta sample, with illuminant D65. The colour differences among Control sample and samples with different levels of GPF were expressed as ΔE, calculated using the following equation:

$$\Delta E = \sqrt{(L_x - L_0)^2 + (a_x - a_0)^2 + (b_x - b_0)^2}$$

where subscript “x” indicates the gluten free pasta formulated with 5 or 10% GPF and the subscript “0” indicates the Control.

2.2.2. Technological properties of pasta

Optimal cooking time (OCT) was determined by following the American Association of Cereal Chemists (AACC, 2000) method 66-50.01. OCT is defined as the time required for the ‘white core’ (ungelatinized starch) in a dough sample to disappear, observed by manually crushing it between two slides. To determine the optimal cooking time samples, 25 g of sample was cooked in 300 mL of boiling distilled water. Complete gelatinization of the starch was verified by taking an aliquot of dough every 30 s.

Water absorption index (WAI) was determined following the method used by Giménez et al. (2013). WAI is calculated by comparing the weight of the cooked pasta with the initial weight of the uncooked pasta.

Table 1
Code for sample and formulation of the gluten free pasta dough.

Samples description	Code	Gluten free mix (g)	GPF (g)	Water (g)	Fresh (F) or dried (D)
Control fresh gluten free pasta	CTPF	250	-	136	F
Control dried gluten free pasta	CTPD	250	-	136	D
Gluten free fresh pasta with 5% of GPF	V5PF	237.5	12.5	141	F
Gluten free dried pasta with 5% of GPF	V5PD	237.5	12.5	141	D
Gluten free fresh pasta with 10% of GPF	V10PF	225	25	145.8	F
Gluten free dried pasta with 10% of GPF	V10PD	225	25	145.8	D

GPF grape pomace flour.

For the analysis, 25 g of the sample was cooked at the optimal cooking time in a beaker containing 300 mL of distilled water placed on a hot plate at 300 °C. After cooking, pasta sample was drained for 3 min using a sieve, then weighed. Water absorption was calculated using the following formula:

$$\text{WAI (\%)} = [(\text{weight of cooked pasta} - \text{weight of uncooked pasta}) / \text{weight of uncooked pasta}] \times 100$$

Cooking loss (CL) was determined according to the method described by Giménez et al. (2013). Cooking loss measures the release of solids from the dough into the cooking water. Before performing the analysis, the beaker was placed in an oven at 105 °C until constant weight was reached. For CL determination, 25 g of sample was cooked at the optimal cooking time in a beaker with 300 mL of distilled water placed on a hotplate at 300 °C. After cooking, the residual water was left in an oven at 105 °C for 24 h. Subsequently, the weight of the beaker with the solid residue was noted. The cooking loss was calculated using the following formula:

$$\text{CL (\%)} = [(\text{Beaker weight with residue} - \text{Empty beaker weight}) / \text{Raw sample weight}] \times 100$$

2.3. Statistical analysis

Data were expressed as the mean value \pm standard deviation. The effects of adding GPF to gluten-free pasta and the drying processes were considered for each parameter. Results were subjected to one-way analysis of variance (ANOVA) using Minitab™ 19 statistical software (Minitab, State College, PA, USA). Significant differences ($p < 0.05$) between samples were evaluated by Tukey's Honestly Significant Difference (HSD).

3. Results and discussion

3.1. Grape pomace properties

The flour yield from pomace was less than 20% due to weight loss during the drying, destemming, and deseeding processes. GPF had a low moisture content (2.13 ± 0.41 g/100 g), similarly to the value reported by Sousa et al. (2014) for Benitaka pomace flour (3.33 ± 0.04 g/100 g). Additionally, GPF exhibited a low pH (3.59 ± 0.02) and high levels of total acidity (12.32 ± 0.45 g/100 g DW). These characteristics, in addition to the low moisture levels, ensure great stability against microbial growth and product safety (Lima et al., 2023). Iora et al. (2015) reported lower acidity levels in Merlot, Tanat, and Cabernet Sauvignon pomace (3.59 – 3.77 g/100 g).

High levels of bioactive compounds characterize GPF. The determined TPC was about 1773.52 ± 207.24 mg GAE/100 g DW and a TAC was about 72.38 ± 16.17 mg/100 g DW, confirming the potential health benefits of this waste product. Ruberto et al. (2007) reported high TPC and TAC values in methanolic extracts of Nerello Mascalese and Nerello Cappuccio pomace (12.36 – 49.33 mg/g and 9.10 – 45.27 mg/g, respectively) and it was found that Nerello Cappuccio had levels of bioactive compounds 4–5 times higher than Nerello Mascalese. It is well known that both polyphenols and anthocyanins content can be significantly affected by factors such as grape variety, year of production and climate, as well as grape pomace processing techniques (e.g., drying, freeze-drying) and extraction methods (Monteiro et al., 2021; La Gatta et al., 2023). GPF exhibited high level of total dietary fibre of about 64.1 ± 5.02 g/100 g DW, characterized by 8.2 ± 1.2 g/100 g of soluble and 55.6 ± 3.22 g/100 g of insoluble fibre. Other author reports lowest fibre levels in red grape pomace of different varieties with a range of about 51–59 % (Beres et al., 2019; Angilè et al., 2025).

Finally, GPF demonstrated high water and oil binding capacities

(WBC: $420.38 \pm 15.75\%$; OBC: $340.63 \pm 57.97\%$), likely due to its fibre content, which is rich in hydroxyl groups (Anil, 2007). These values exceeded those observed by Baldán et al. (2021) in Syrah pomace dried at 55 °C, suggesting that GPF has the potential to improve pasta texture and rheology. Optimising the level of hydration when re-formulating pasta is essential. This has a direct impact on the characteristics of the dough, especially during the extrusion phase, and the quality of the final product. (Bresciani et al., 2022).

3.2. Gluten-free pasta

3.2.1. Moisture content and cooking quality

Adding GPF to the gluten-free pasta formulation increased the amount of water required due to its high WBC. The quantity of water used was that required for extruding pasta (Table 1). Control fresh samples (CTPF) had a moisture level of about 40% and samples with 5 or 10% of GPF significantly increased their moisture up to about 42% (Table 2) due to the increased level of water in the formulation. Following the drying process, the moisture content decreased in all gluten free pasta samples. The reduction was more pronounced in samples containing GPF (Table 2) probably due to the presence of fibre which promotes faster water loss during drying. Santos et al. (2025) observed that, during the drying of pasta with different levels of fibre at 45°, 55 °C and 65 °C the higher the fibre content, the longer the time to dry. However, at 55 °C sample without fibre added had the longest time to dry.

As concern OCT, fresh pasta exhibited the shortest cooking time, whereas the dried pasta required the longest. The addition of grape pomace flour did not significantly affect the OCT of fresh gluten-free pasta, with a mean value of about 2:25 min suggesting that the structure of GPF fortified gluten free pasta is similar to the control (CTPF) (Lorenzo et al., 2018). In contrast, OCT of dried pasta significantly increased in samples with GPF, independently from the percentage of the added GPF. Dried control pasta sample (CTPD) showed an OCT about 5:10 min, while the maximum OCT value observed was about 7:10 min for V10PD. This indicates that water diffusion within the pasta matrix is more difficult due to insoluble particles physically hindering movement. Consequently, a stronger network, is formed suggesting that the structure of these samples is similar to or improved compared to that of the control recipe (Lorenzo et al., 2018).

Table 2

Yield, Moisture, Optimal Cooking Time (OCT), Cooking Loss (CL) and Water Absorption Index (WAI) of gluten-free pasta from control and fortified.

Samples	Moisture (%)	OCT ^a (min)	CL ^c (%)	WAI ^b (%)
CTPF	39.97 \pm 0.56	02:20 \pm 0.01	7.12 \pm 2.61	72.91 \pm 3.54
	cA	aB	aA	abB
CTPD	5.12 \pm 0.12	05:10 \pm 0.01	9.48 \pm 0.38	165.28 \pm 5.10
	aB	bA	bA	aA
V5PF	42.05 \pm 0.31	02:50 \pm 0.01	6.21 \pm 1.10	78.96 \pm 2.79
	aA	aB	aA	aB
V5PD	3.86 \pm 0.57	07:00 \pm 0	10.53 \pm 1.97	165.32 \pm 2.52
	bB	aA	bA	aA
V10PF	41.07 \pm 0.12	02:10 \pm 0.01	6.45 \pm 1.49	63.26 \pm 6.27
	bA	aB	aB	bB
V10PD	3.80 \pm 0.20	07:10 \pm 0.01	19.36 \pm 1.25	156.37 \pm 8.64
	bB	aA	aA	aA

Data are showed as mean \pm SD. Mean values followed by different lowercase letters, between fresh (F) or dried (D) samples, are significantly different (p -value < 0.05). Mean values followed by different capital letters, between samples with the same formulation, are significantly different (p -value < 0.05). CTPF control fresh gluten free pasta; CTPD control dried gluten free pasta; V5PF gluten free fresh pasta with 5% of GPF; V5PD gluten free dried pasta with 5% of GPF; V10PF gluten free fresh pasta with 10% of GPF; V10PD gluten free dried pasta with 10% of GPF.

^a Optimal Cooking time.

^b Water Absorption Index.

^c Cooking Loss.

CL is an important parameter for evaluating pasta quality. The main cause of CL is the leaching of gelatinized starch, a process more pronounced in gluten-free products due to the absence of a gluten network (Iuga and Mironeasa, 2020a). As observed for OCT, the incorporation of GPF does not appear to affect CL in fresh samples, with a mean value about 7%. A CL value less than 9% is the technologically accepted limit for dry pasta (AACC, 2000). In the dried gluten-free pasta samples CL significantly increase respect to the fresh one. Similar values of CL were observed for CTPD and VSPD, but when the GPF was added at 10% a notable increase of the CL parameter (about 19.36) was determined, probably due to the high fibre content which may cause more gelatinized starch leaching (Iuga and Mironeasa, 2020a). A similar trend was reported in gluten-free pasta, the increase in CL was related to the weakening of the starch network due to the presence of fibre (Cabrera-Chávez et al., 2012; Bayrakçı and Bilgiçli, 2024). Moreover, fibre promotes the leaching of starch, more accentuated in gluten-free products due to the gluten network absence (Iuga and Mironeasa, 2020a and references therein). To mitigate CL in gluten-free pasta, supplementation of the protein fraction—such as whey powder or egg white—could be beneficial, as it aids in forming a structure capable of retaining starch (Iuga et al., 2020b). The trend between cooking time and cooking loss can be explained by the fact that both cooking time and cooking loss are strongly influenced by the structural changes that occur during starch gelatinization. As the fibre-rich matrix increases the resistance to water penetration, the pasta requires longer cooking times.

Meanwhile, the weakened starch network facilitates the release of solids into the cooking water, thereby indirectly linking the two parameters (Sobota and Zarzycki, 2012).

The drying processes of gluten-free pasta significantly influences the WAI values of samples. Fresh samples with the highest moisture absorb less water (WAI values 63-73%) and the addition of GPF does not induce changes in this parameter. Dried samples showed the highest WAI value ranging from about 156 to 165%. No significant differences ($p > 0.05$) between control and gluten-free fettuccine with 5% GPF was found. It was reported that when fibre competes with starch for water during pasta formation, this reduces starch swelling and consequently pasta water absorption (Foschia et al., 2015; Iuga et al., 2020b). A decrease in WAI with the increase of rice bran fibre (RBF) levels in rice pasta was reported due both to a relative decrease in starch content and to competition for water absorption between the RBF and the starch (Wang et al., 2018). Similar WAI percentage was found by Flores-Silva et al. (2015) in gluten-free spaghetti. Factors such as the type of flour used, processing conditions and the presence of ingredients such as fibre and can influence WAI (Flores-Silva et al., 2015). In any case, based on the range established by Bustos et al. (2015) (WAI: 150–200 g water/100 g pasta), all analysed pasta samples can be classified as excellent in quality.

The colour of a food product is the first factor that influences consumer's decisions to purchase it. Fig. 2 show the gluten free pasta samples, obtained with different levels of GPF. Control samples both fresh



Fig. 2. Fresh and dried gluten-free pasta samples. (A) Fresh control; (B) Dried control; (C) Fresh pasta with 5% GPF; (D) Dried pasta with 5% GPF; (E) Fresh pasta with 10% GPF; (F) Dried pasta with 10% GPF.

and dried showed the highest L^* and b^* values and the lowest a^* values (Table 3).

The addition of grape pomace flour significantly affected, the $L^*a^*b^*$ coordinates of both fresh and dried pasta: as the percentage of added grape pomace flour increased, the L^* and b^* coordinates decreased, while the a^* coordinate increased. A reduction in L^* indicates a darker colour, an increase in a^* highlighted a redder colour and a decrease in b^* indicates a reduction in yellowness (Table 3).

Drying did not significantly affect the L^* coordinate of the control samples or the a^* and b^* coordinates of the gluten free pasta fortified with 5% and 10% grape pomace flour. However, it significantly affected the L^* coordinate of the pasta fortified with 5% and 10% of GPF, resulting in an increase respect to control sample, probably due to a different starch structural changes that affect the optical properties of the GPF fortified gluten-free pasta (Martí and Pagani, 2013). As for the control pasta, drying significantly affected the a^* coordinate, causing an increase, and the b^* coordinate, causing a decrease.

ΔE values quantify the difference between two colours. A ΔE^* value of 2-3 is the threshold for perceiving a colour difference under standard viewing conditions, while values above 5 are clearly perceptible (Sempio et al., 2025). Values ranging from 15 to 27, were found between the control sample and the gluten free pasta containing 5% and 10% of GPF. This indicates a significant a deep colour difference between the samples which is clearly visible and easily distinguishable to observers. Compared to the clear colour of the control sample (Fig. 2), the fortification gave the pasta a pink hue, and the GPF could be distinguished as pink dots with the naked eye (Fig. 2).

3.2.2. Chemical properties of gluten-free pasta

The addition of GPF significantly increase the TPC of fresh and dried gluten-free pasta (Table 4). Obviously, as the percentage of GPF increased, the TPC increased, resulting the highest in V10PF pasta (Table 4).

There are no specific studies in the literature evaluating the TPC of gluten-free pasta fortified with grape pomace. However, some studies reported that fortifying gluten-free pasta with polyphenol-rich matrices leads, as expected, to an increase in TPC. For instance, Oniszczuk et al. (2019) found that enriching gluten-free pasta with chestnut flour resulted in a higher polyphenol content compared to the control. Notably, the pasta containing the highest percentage of chestnut flour (50%) exhibited the highest TPC levels.

Drying did not significantly affect the TPC of the control sample, but it had a significant impact on both the fortified samples at 5% and 10%,

Table 3
Gluten-free pasta color parameters.

Samples	L^*	a^*	b^*	C	h
CTPF	90.91 ± 0.58 a A	-1.98 ± 0.20 c B	9.91 ± 1.19 a A	10.11 ± 1.20 aA	101.39 ± 0.5 aA
	91.59 ± 1.41 a A	-1.25 ± 0.11 c A	7.84 ± 0.33 a B	7.94 ± 0.34 aB	99.05 ± 0.53 aB
V5PF	74.93 ± 2.01 b B	5.02 ± 0.59 b A	4.74 ± 0.51 b A	6.90 ± 0.75 cA	43.35 ± 1.69 bA
	78.37 ± 1.25 b A	4.65 ± 0.47 b A	4.34 ± 0.94 b A	6.38 ± 0.95 bA	42.45 ± 4.44 bA
V5PD	65.79 ± 4.52 c B	7.21 ± 1.39 a A	4.18 ± 2.27 b A	8.24 ± 1.90 bA	26.56 ± 9.30 cA
	71.59 ± 2.67 c A	6.35 ± 1.07 a A	3.9 ± 1.69 b A	7.52 ± 1.67 aA	29.46 ± 10.37 cA

Data are showed as mean ± SD. Mean values followed by different lowercase letters, between fresh (F) or dried (D) samples, are significantly different (p-value <0.05). Mean values followed by different capital letters, between samples with the same formulation, are significantly different (p-value <0.05). CTPF control fresh gluten free pasta; CTPD control dried gluten free pasta; V5PF gluten free fresh pasta with 5% of GPF; V5PD gluten free dried pasta with 5% of GPF; V10PF gluten free fresh pasta with 10% of GPF; V10PD gluten free dried pasta with 10% of GPF.

Table 4

Total Polyphenol Content (TPC), Total Anthocyanin Content (TAC), pH, Titratable Acidity (TA), of gluten-free pasta from control and fortified.

Samples	TPC (mgGAE/100 g DW)	TAC (mg/kg DW)	pH	Acidità titolabile (gTA/kg)
CTPF	37.55 ± 6.42 c A	-	6.28 ± 0.04 a A	1.25 ± 0 c A
CTPD	40.81 ± 6.49 c A	-	6.22 ± 0.01 a A	1.18 ± 0 c A
V5PF	194.21 ± 3.83 b A	40.78 ± 0.68 b A	3.89 ± 0.04 b A	8.18 ± 0.36 b A
	93.69 ± 6.20 b B	31.73 ± 3.60 b B	3.83 ± 0.02 b A	8.29 ± 0.25 b A
V10PF	227.74 ± 2.87 a A	88.05 ± 4.14 a A	3.7 ± 0.09 c A	15.46 ± 0.32 a A
	132.23 ± 8.21 a B	62.75 ± 4.32 a B	3.67 ± 0.05 c A	26.26 ± 0.90 a B

Data are showed as mean ± SD of three replicates. Mean values followed by different lowercase letters, between fresh (F) or dried (D) samples, are significantly different (p-value <0.05). Mean values followed by different capital letters, between samples with the same formulation, are significantly different (p-value <0.05). CTPF control fresh gluten free pasta; CTPD control dried gluten free pasta; V5PF gluten free fresh pasta with 5% of GPF; V5PD gluten free dried pasta with 5% of GPF; V10PF gluten free fresh pasta with 10% of GPF; V10PD gluten free dried pasta with 10% of GPF.

leading to a reduction in polyphenol content. In any case the addition of GPF even at the lowest level allowed to obtain a gluten-free pasta richer than control sample in polyphenols. In the control sample, anthocyanins were absent, as corn and rice do not naturally contain these compounds. The addition of grape pomace flour significantly influenced the TAC of both fresh and dried pasta, resulting in an increase (Table 3). As the percentage of added grape pomace flour increased, TAC levels also rose, with the highest value observed in the pasta containing 10% GPF (SG V10PF) (Table 3). Furthermore, drying significantly affected the TAC of gluten free pasta fortified with GPF, resulting in a reduction (Table 3). The dried pasta exhibited lower anthocyanin content than its fresh samples, as anthocyanins, analogously to polyphenols, are sensitive to heat (Sólyom et al., 2014). Bioavailability of phenolic compounds depends on processing loss and absorption. Moreover, the presence of fibre, carbohydrates, proteins and other constituents may influence the bioavailability of phenolic compounds. Also cooking could modify the bioaccessibility of different phenolic compound subclasses. Moreover, it was reported that cyanidine-3-O-glucoside produces bioactive metabolites in the gastrointestinal tract, contributing to intestinal integrity and function. This suggests that phenolic bioavailability should consider native compounds and metabolites (Melini et al., 2020 and references therein). The incorporation of grape pomace flour also had a considerable impact on the pH and acidity of both fresh and dried gluten-free pasta (Table 3). As the proportion of pomace flour increased, the acidity levels rose and the pH decreased. The control pasta samples displayed lower acidity and higher pH values than the fortified samples. Among the fortified samples, SG V10PE gluten free pasta exhibited the highest acidity and the lowest pH. Baldán et al. (2021) reported a higher pH (6.62 ± 0.06%) in muffins containing 15% pomace flour and lower acidity (0.0610 ± 0.0004 gTA/100 g) than the 10% fortified gluten-free pasta analysed in the present research. Probably, the presence of other ingredients in the muffin's formulation contributes to mitigating the acidity of pomace flour. According to FDA guidelines, the 5% and 10% fortified pasta samples can be considered microbiologically safe against *Clostridium botulinum*.

Considering a serving size of about 150 g of fresh pasta, adding of 5% GPF produced gluten free fettuccine with a TPC content of about 169.8 mg GAE, a TAC of 35.4 mg, and a total fibre content of about 3.1 g. Increasing the addition of GPF to 10% resulted in an increased intake of bioactive compounds of 201.3 mg for TPC, 77.8 mg for TAC and for 6.1 g for fibre. In contrast, consuming control pasta provides only 33.8 mg of

TPC. Considering that the TPC intake from pasta is reported to be about 45.5 mg (Pérez et al., 2023), gluten free pasta samples, even those with the lowest level of fortification, provide a noticeable amount of these bioactive compounds. In terms of TAC, a serving size of red grapes provides an intake of approximately 42.7 mg (Wu et al., 2006), which is similar to the intake from consuming V5PF samples, but lower than that from V10PF samples. Furthermore, consumption of both gluten free pasta samples provides an additional fibre intake, considering that gluten free foods generally lack in this nutritional compound.

4. Conclusion

The incorporation of grape pomace flour significantly influenced the nutritional, technological, and physicochemical properties of gluten-free pasta. Enriching the pasta with grape pomace led to a substantial increase in polyphenols and anthocyanins content, well known for their antioxidant effects. It also increased the pasta's fibre content, which gluten-free foods generally lack.

From a technological standpoint, OCT increased in dried samples with GPF and increase with the drying process. At the same time CL was similar in fresh gluten free pasta, regardless of the presence of GPF. However, the drying process induced an increase in samples with 10% of GPF. WAI was only influenced by the drying process with the highest value determined in dried samples independently from the amount of GPF added. Among the tested formulations, pasta fortified with 10% grape pomace flour exhibited the best overall performance in terms of nutritional profile. This fortification strategy supports both the principles of the circular economy and the concept of circular gastronomy, in which, by-products are reintroduced into the food chain through health oriented culinary innovation. This reduces waste and creates new business opportunities in the food sector.

These results provide a basis for future studies to evaluate sensory analysis of GPF gluten free pasta and consumers acceptance, the changes induced by cooking in bioactive compounds and their bioaccessibility.

CRedit authorship contribution statement

Daniele Catanzaro: Writing – original draft, Visualization, Investigation, Formal analysis, Data curation. **Biagio Fallico:** Writing – review & editing, Supervision, Conceptualization. **Elena Arena:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Funding acquisition, Conceptualization.

Implications for gastronomy

Red grape pomace is an innovative ingredient in gastronomy, naturally rich in fibre, polyphenols, and anthocyanins. As a by-product of the winemaking process, its incorporation into gluten-free pasta, typically low in fibre and bioactive compounds, adds valuable nutritional benefits while supporting sustainable culinary innovation. Adding grape pomace enhances the gluten free pasta's nutritional profile, a deep violet colour, and increased water and oil absorption capacity, thereby improving sauce retention. These characteristics open new culinary possibilities, ranging from modern interpretations of traditional dishes to gourmet creations that emphasize colour, contrast, and sustainability. The fortified pasta is also versatile beyond traditional boiling; it can be used in baked or stuffed dishes, or even as a base for functional snacks. Thanks to the presence of phenolic compounds, the product improves in both nutritional value and colour, making it ideal for contemporary fine dining and sustainable innovation in the food gastronomy.

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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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