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IMPACT OF PARTIAL SUBSTITUTION OF WHEAT FLOUR WITH CHESTNUT FLOUR AND CHOKEBERRY (*Aronia melanocarpa*) POWDER ON THE NUTRITIONAL, FUNCTIONAL AND COOKING QUALITY OF PASTA

Daniela STOIN[1], Calin JIANU[1], Ersilia ALEXA[1], Mariana-Atena POIANA[1], Ariana-Bianca VELCIOV[1], Sylvestre DOSSA[1], Corina MEGYESI[1], Diana MOIGRADEAN[1], Christine (NEAGU) DRAGOMIR[1], Carmen Daniela PETCU[2]

[1]University of Life Sciences "King Mihai I" from Timisoara, Faculty of Food Engineering, 119 Calea Aradului Street, 300645, Timisoara, Romania
[2]University of Agronomic Sciences and Veterinary Medicine of Bucharest, Faculty of Veterinary Medicine, 105 Splaiul Independentei, District 5, 050097, Bucharest, Romania

Corresponding author email: marianapoiana@usvt.ro

Abstract

This study aimed to evaluate the potential of chestnut flour (CF) and chokeberry powder (CP) as alternative sources of bioactive compounds for the development of pasta formulations with improved nutritional and functional properties. Four pasta formulations were obtained by partially replacing wheat flour (WF) with CF at levels of 0%, 10%, 20%, and 30%. In addition, three formulations were produced by further substituting wheat flour in the 20% CF sample with CP at levels of 2%, 4%, and 6%. The samples were analyzed for proximate composition, total phenolic content (TPC), antioxidant activity (DPPH assay), and cooking quality. Substitution of WF with CF at 10–30% resulted in significant improvements in nutritional and phytochemical profiles of pasta while maintaining acceptable cooking quality. Further substitution of wheat flour in the 20% CF formulation with CP up to 4% led to a marked increase in bioactive compounds and is therefore recommended for enhancing pasta functionality without compromising cooking quality. These findings support the use of CF and CP as functional ingredients for the development of innovative flour-based products.

Key words*: chestnut flour, chokeberry powder, cooking quality, functional pasta, nutritional profile.*

INTRODUCTION

Pasta is one of the most widely consumed cereal-based foods, valued for its versatility, technological stability, and sensory acceptability. Its quality largely depends on the formation of a compact starch–protein network during dough processing and cooking, which determines texture and cooking behaviour (Dziki, 2021; Brochard et al., 2021). Despite these advantages, conventional pasta is often regarded as nutritionally limited, as it is typically produced from refined wheat flour with reduced fibre and bioactive compound content (Dziki, 2021). For this reason, increasing research attention has been directed toward enriching pasta with plant-derived ingredients that improve nutritional value while maintaining technological performance. Owing to its structural stability and formulation flexibility, pasta represents a suitable carrier for functional ingredients (Littardi et al., 2020).

Among alternative raw materials, chestnut flour has received growing attention due to its distinctive nutritional profile and functional properties. It provides complex carbohydrates and resistant starch, moderate levels of dietary fiber (commonly around 4-10 g/100 g), and relatively low lipid content dominated by unsaturated fatty acids. In addition, chestnut flour supplies vitamins (B-group, C, and E), essential minerals such as potassium and magnesium, and phenolic compounds associated with antioxidant activity (Demirkesen et al., 2010; Littardi et al., 2020; Ciucure et al., 2022; Alinovi et al., 2023; Stoin et al., 2025). These characteristics support its use as a fortifying ingredient that can enhance fibre, mineral, and phytochemical content in cereal-based foods (Dall'Asta et al., 2013; Oniszczuk et al., 2019; Pop et al., 2025; Stoin et al., 2025). Its application has been explored in a wide range of products, including bread (Raczyk et al., 2021), cookies (Sharma & Devi, 2021),

muffins (Choi et al., 2024) and pasta (Littardi et al., 2020), where moderate substitution levels generally improve nutritional quality and antioxidant potential. However, because chestnut flour is naturally gluten-free, its incorporation can alter dough rheology and structural integrity, highlighting the need for careful formulation to balance functional benefits and technological performance (Altıner & Mete, 2020; Raczyk et al., 2021; Pop et al., 2025).

Alongside alternative flours, fruit-derived ingredients rich in polyphenols have gained interest as natural fortifying agents. Chokeberry (*Aronia melanocarpa*) is widely recognized for its exceptionally high polyphenol content, particularly anthocyanins and related phenolic compounds, as well as for its contribution of vitamins, minerals, and dietary fibre. The incorporation of chokeberry-derived ingredients into cereal matrices has been associated with increased total phenolic content and enhanced antioxidant capacity, commonly evaluated using assays such as DPPH and FRAP (Adamczyk et al., 2025; Stoin et al., 2025). Importantly, relatively low inclusion levels can provide meaningful phytochemical enrichment while maintaining acceptable technological and sensory properties, whereas excessive addition may negatively affect colour and flavour (Stoin et al., 2025). Taken together, these findings support the potential of combining chestnut flour with chokeberry powder as a strategy for developing value-added cereal products with improved nutritional density and bioactive profiles. This approach allows simultaneous enhancement of fibre and mineral content through chestnut flour and polyphenol enrichment through chokeberry-derived compounds, while still requiring careful formulation to preserve product quality (Demirkesen et al., 2010; Pop et al., 2025; Stoin et al., 2025).

In this context, the present study investigated the combined use of chestnut flour and chokeberry powder as functional ingredients for the development of nutritionally enhanced pasta. Wheat flour was partially substituted with chestnut flour to improve fibre content and micronutrient density, followed by the incorporation of chokeberry powder as a natural source of polyphenols and antioxidant compounds (Borczak et al., 2023; Krajewska & Dziki, 2023). The resulting formulations were evaluated in terms of nutritional composition, antioxidant capacity, and key cooking quality parameters to better understand the relationship between functional enrichment and technological performance. By integrating nutrient-dense flour substitution with polyphenol-rich fruit fortification, this study provides insights into the formulation of value-added pasta with improved functional attributes while maintaining quality characteristics relevant to consumer acceptance and processing applicability.

MATERIALS AND METHODS

Raw materials and formulation design

For pasta production, the following raw materials were used: wheat flour type 000 (WF) with a moisture content of 13.72% (Boromir, Romania), chestnut flour (CF) produced by Targroch, and chokeberry powder (CP) produced by Dragon Superfoods purchased from a local natural products store in Timișoara, Romania. Wheat flour type 000 was selected instead of durum wheat semolina due to its fine particle size, comparable to that of CF and CP. Prior to use, CF and CP were sieved through an 80-mesh sieve to standardize particle size. Salt and potable water from local commercial sources were also included in the dough formulation. Two sets of composite flours were prepared through partial substitution of WF. In the first set, WF was replaced with CF at levels of 0% (control), 10%, 20%, and 30%, resulting in the CF0-CF30 blends. In the second set, a portion of WF in the 20% CF formulation (CF20) was further replaced with CP at levels of 2%, 4%, and 6%, yielding the CF20CP2-CF20CP6 blends. Pasta samples prepared from these blends were coded as PCF0 (control), PCF10, PCF20, and PCF30 for Group I, and PCF20 (control), PCF20CP2, PCF20CP4, and PCF20CP6 for Group II.

Pasta production process

Pasta samples were prepared following a conventional technological process adapted from the procedures described by Brochard et al. (2021) and Stoin et al. (2024). The dry ingredients (WF, CF, CP, and salt) were weighed and blended according to each experimental formulation to obtain a homogeneous mixture. Salt was incorporated at a level of 2 g per 100 g of flour blend. Tap water

(55 mL per 100 g flour) was added gradually, and the mixture was kneaded by hand for 10 min until a firm, uniform dough was obtained (Table 1). The dough was then allowed to rest for 1 h at room temperature (approximately 25°C), covered with plastic wrap to prevent surface drying. After resting, the dough was sheeted using a pasta machine (Marcato Ampia 150, Italy) to a uniform thickness of 2 mm. Drying was performed in a cabinet dryer (Italgi S.R.L., Italy) at 40 °C for approximately 12 h, until a final moisture content of about 11% was reached. The dried pasta was portioned (300 g), sealed in polypropylene bags, and stored at room temperature (25°C) for 60 days prior to analysis. Each formulation was prepared in triplicate (n = 3).

Table 1. Pasta formulations: control sample and variants fortified with CF or with CF and CP

Pasta formulations	Ingredients (%)				
	WF	CF	CP	S	W
	Pasta formulations (Set I)				
PCF0	100	0	0	2	55
PCF10	90	10	0	2	55
PCF20	80	20	0	2	55
PCF30	70	30	0	2	55
	Pasta formulations (Set II)				
PCF20	80	20	0	2	55
PCF20CP2	78	20	2	2	55
PCF20CP4	76	20	4	2	55
PCF20CP6	74	20	6	2	55

WF - Wheat flour; CF - chestnut flour; CP: chokeberry powder**;** PCF0 – Control pasta (100% wheat flour (WF): 0% chestnut flour (CF); PCF10 – Pasta sample with 90% wheat flour (WF): 10% chestnut flour (CF); PCF20 – Pasta sample with 80% wheat flour (WF): 20% chestnut flour (CF); PCF30 – Pasta sample with 70% wheat flour (WF): 30% chestnut flour (CF); PCF20CP2 – Pasta sample with 78% wheat flour (WF): 20% chestnut flour (CF): 2% chokeberry powder (CP); PCF20CP4 – Pasta sample with 76% wheat flour (WF): 20% chestnut flour (CF): 4% chokeberry powder (CP); PCF20CP6 – Pasta sample with 74% wheat flour (WF): 20% chestnut flour (CF): 6% chokeberry powder (CP).

Proximate composition of raw materials and pasta samples

The proximate composition of both raw materials and pasta samples was determined following standard analytical procedures of the Association of Official Analytical Chemists (AOAC, 2005). Moisture content was determined gravimetrically by oven-drying samples at 105°C until constant weight was achieved (AOAC 925.10). Protein content was quantified by the Kjeldahl method (AOAC 990.03), using a nitrogen-to-protein conversion factor of 5.70, as recommended for wheat-based products. Fat content was determined by Soxhlet extraction using petroleum ether as solvent (AOAC 920.39). Total dietary fibre was quantified by an enzymatic-gravimetric method according to AOAC 985.29. Ash content was obtained by incineration at 550°C for 5 h (AOAC 923.03). Total carbohydrate content was calculated by difference according to Equation (1), following the approach reported by Borșa et al. (2025):

$$\text{Total carbohydrates (\%)} = 100 - [\text{lipids (\%)} + \text{proteins (\%)} + \text{ash (\%)} + \text{moisture (\%)}] \quad (1)$$

The energy value was estimated using Atwater conversion factors (9 kcal/g for fat, 4 kcal/g for protein, and 4 kcal/g for carbohydrates), as shown in Equation (2):

$$\text{Energy value (kcal/100 g)} = 9 \times \text{fat (\%)} + 4 \times \text{carbohydrates (\%)} + 4 \times \text{proteins (\%)} \quad (2)$$

All analyses were performed in triplicate on both flour blends and finished pasta samples.

Cooking quality of pasta

Pasta cooking quality was evaluated based on established methods reported in previous studies (Chetrariu & Dabija, 2021; Schettino et al., 2021; Littardi et al., 2020). The optimum cooking time (OCT) was determined by cooking 25 g of pasta in 300 mL of boiling water without salt addition. At 30 s intervals, a pasta strand was pressed between two glass plates, and the OCT was defined as the complete disappearance of the starchy central core (Schettino et al., 2021). Determinations were performed in duplicate.

Cooking loss (CL) was evaluated gravimetrically by boiling 10 g of dried pasta in 200 mL of deionised water for the duration of the OCT. The cooking water was collected and evaporated to dryness at 105°C, and the residue was expressed as a percentage of the initial dry pasta weight, following gravimetric procedures adapted from Littardi et al. (2020).

Water absorption (WA) was calculated from the weight of pasta before and after cooking at the optimal cooking time and expressed as g per 100 g of dry pasta (Chetrariu & Dabija, 2021), according to Equation (3):

$$WA = [(w - w_0) / w_0] \times 100 \quad (3)$$

where w and w_0 represent the weights of cooked and raw pasta, respectively.

The swelling index (SI) was calculated as the ratio between the weight of cooked and

uncooked pasta. All measurements were performed in triplicate.

Preparation of Alcoholic Extracts

All analyses were conducted on dried pasta samples, with results reported on a dry-weight basis. Alcoholic extracts were prepared for the assessment of total phenolic content and antioxidant activity, based on the procedure described by Stoin et al. (2025), with minor adaptations for dried pasta matrices. Approximately 1.0 g of finely ground dried pasta was combined with 10 mL of 70% ethanol (*v/v*) and stirred for 2 h at room temperature using a magnetic stirrer. The suspension was then centrifuged at 10.000 rpm for 10 min, and the supernatant was carefully collected. The remaining residue underwent a second extraction with 70% ethanol for an additional 1 h under continuous stirring, followed by centrifugation under identical conditions. The pooled supernatants were stored at −20°C in the dark until further analysis. All samples were prepared and analysed independently in triplicate.

Total Phenolic Content (TPC)

Total phenolic content was determined using the Folin–Ciocalteu method as described by Stoin et al. (2025). Before analysis, alcoholic extracts were diluted 1:5 (v/v) with distilled water. A 0.5 mL aliquot of the diluted extract was mixed with 2.5 mL of Folin–Ciocalteu reagent and left to react for 5 min at room temperature. Subsequently, 2 mL of 7.5% Na_2CO_3 solution was added, and the mixture was incubated at 50 °C for 30 min. Absorbance was recorded at 750 nm using a UV–Vis spectrophotometer, using a reagent blank as reference. Results were expressed as milligrams of gallic acid equivalents per 100 g dry weight (mg GAE/100 g d.w.), calculated from a gallic acid calibration curve ($R^2 > 0.999$). All determinations were performed in triplicate.

Antioxidant Activity (DPPH Assay)

The free radical scavenging activity of the samples was determined using the DPPH (2,2-diphenyl-1-picrylhydrazyl) assay, following the protocol described by Pop et al. (2025). A 0.1 mM DPPH working solution was prepared in 70% (*v/v*) ethanol. Before analysis, extracts obtained from wheat flour (WF), chestnut flour (CF), and pasta samples were diluted with 70% (v/v) ethanol at a ratio of 1:5 (*v/v*), while the chokeberry powder (CP) extract was diluted at a ratio of 1:100 (*v/v*).

A 1.0 mL aliquot of each diluted extract was mixed with 2.5 mL of the DPPH solution and incubated in the dark at 20°C for 30 min. Absorbance was measured at 517 nm using 70% ethanol as the blank. A control sample was prepared under identical conditions by replacing the extract with 1.0 mL of 70% ethanol.

DPPH scavenging activity (%) was calculated using the following equation (4):

$$\text{DPPH scavenging activity (\%)} = \frac{A_{control} - A_{sample}}{A_{control}} x100 \quad (4)$$

where *A_control* represents the absorbance of the control and *A_sample* represents the absorbance of the sample.

To quantify antioxidant activity, DPPH scavenging activity values were plotted against Trolox standard concentrations (1.0–25 µg/mL) to generate a calibration curve. Results were expressed as µmol Trolox equivalents per gram of dry weight (µmol TE/g d.w.). All determinations were performed in triplicate.

Statistical analysis

Experimental data were collected from three independent replicates, each performed in triplicate, and are expressed as mean ± standard deviation (SD). Prior to statistical analysis, the assumptions of normality, homogeneity of variances (assessed via Levene's test), and independence of observations were verified and confirmed. Differences among formulations were evaluated by one-way analysis of variance (ANOVA), followed by Tukey's post hoc test for multiple comparisons, with statistical significance set at $p < 0.05$.

RESULTS AND DISCUSSIONS

Proximate composition of raw materials and pasta formulations

The proximate composition of the raw materials (WF, CF, and CP) and pasta formulations (Set I and Set II) is presented in Table 2. Moisture content differed significantly ($p < 0.05$) among samples, with WF showing the highest value (12.72%), followed by CF (10.59%) and CP (7.62%). The lower moisture content of CP may contribute to improved shelf-life.

Table 2. Proximate composition and energy value of raw materials and pasta formulations

Samples	Chemical Parameters						Energy value (kcal/ 100 g)
	Moisture (%)	Fat (%)	Protein (%)	Ash (%)	*CRB (%)	Fiber (%)	
Raw materials							
WF	12.72±0.14^{a}	1.47±0.03^{c}	12.74±0.04^{a}	0.58±0.08^{c}	72.49±0.02^{c}	3.39±0.03^{c}	354.15±0.06^{c}
CF	10.59±0.15^{b}	3.88±0.09^{b}	7.67±0.02^{b}	3.07±0.09^{b}	74.79±0.08^{b}	7.12±0.09^{b}	364.76±0.04^{b}
CP	7.62±0.11^{c}	4.55±0.04^{a}	6.46±0.05^{c}	4.19±0.11^{a}	77.18±0.04^{a}	16.69±0.11^{a}	375.51±0.03^{a}
Pasta formulations (Set I)							
PCF0	12.24±0.02^{a}	1.22±0.04^{d}	9.68±0.02^{a}	0.55±0.04^{d}	76.31±0.03^{a}	2.58±0.05^{d}	354.94±0.05^{d}
PCF10	12.08±0.03^{b}	1.49±0.03^{c}	9.46±0.04^{b}	0.80±0.03^{c}	76.16±0.03^{b}	3.03±0.02^{c}	355.92±0.06^{c}
PCF20	11.91±0.02^{c}	1.75±0.05^{b}	9.28±0.05^{c}	1.05±0.07^{b}	76.01±0.04^{c}	3.49±0.02^{b}	356.89±0.04^{b}
PCF30	11.75±0.03^{d}	2.02±0.07^{a}	9.09±0.07^{d}	1.31±0.02^{a}	75.85±0.02^{d}	3.94±0.03^{a}	357.87±0.05^{a}
Pasta formulations (Set II)							
PCF20	11.91±0.02^{a}	1.75±0.05^{a}	9.28±0.05^{a}	1.05±0.07^{a}	76.01±0.04^{a}	3.49±0.02^{d}	356.89±0.04^{d}
PCF20CP2	11.82±0.03^{b}	1.81±0.02^{a}	9.22±0.02^{a}	1.11±0.05^{a}	76.03±0.12^{a}	3.75±0.06^{c}	357.28±0.22^{c}
PCF20CP4	11.74±0.03^{c}	1.86±0.06^{a}	9.17±0.02^{b}	1.18±0.05^{a}	76.06±0.11^{a}	4.02±0.04^{b}	357.65±0.12^{b}
PCF20CP6	11.65±0.04^{d}	1.92±0.04^{a}	9.11±0.03^{c}	1.24±0.02^{a}	76.08±0.10^{a}	4.28±0.02^{a}	358.03±0.19^{a}

WF - Wheat flour; CF - chestnut flour; CP: chokeberry powder**;** PCF0 – Control pasta (100% wheat flour (WF): 0% chestnut flour (CF); PCF10 – Pasta sample with 90% wheat flour (WF): 10% chestnut flour (CF); PCF20 – Pasta sample with 80% wheat flour (WF): 20% chestnut flour (CF); PCF30 – Pasta sample with 70% wheat flour (WF): 30% chestnut flour (CF); PCF20CP2 – Pasta sample with 78% wheat flour (WF): 20% chestnut flour (CF): 2% chokeberry powder (CP); PCF20CP4 – Pasta sample with 76% wheat flour (WF): 20% chestnut flour (CF): 4% chokeberry powder (CP); PCF20CP6 – Pasta sample with 74% wheat flour (WF): 20% chestnut flour (CF): 6% chokeberry powder (CP). *CRB – carbohydrates. Data are presented as mean ± standard deviation of three independent analyses. Values with different letters within the same column are significantly different (one-way ANOVA, $p < 0.05$), while those with the same letter are not significantly different ($p > 0.05$).

Similar moisture ranges were reported by Stoin et al. (2025) for functional cereal raw materials. Most compositional parameters differed significantly ($p < 0.05$) among samples, as indicated by different superscript letters in Table 2, with the exception of fat, ash, and carbohydrate contents in Set II formulations, which showed no significant differences upon chokeberry powder addition. The three raw materials presented strikingly different nutritional profiles, each contributing distinct functional properties to the final formulations. WF had the highest protein content (12.74%) alongside the lowest ash (0.58%) and fat (1.47%) levels, reflecting the typical composition of a refined cereal dominated by starch and gluten-forming proteins (Dziki, 2021). CF brought a richer mineral and fiber profile, with notably higher fat (3.88%), ash (3.07%), and dietary fiber (7.12%) contents and lower protein levels (7.67%), in agreement with reported ranges for chestnut-derived ingredients (Altıner & Mete, 2020; Torra et al., 2021; Ciucure et al., 2022). CP stood out for its exceptional fiber content (16.69%), the highest among all raw materials, alongside elevated fat (4.55%) and ash (4.19%) values, reflecting the concentrated nature of dried berry-derived powders. This high fiber fraction underlines the potential of CP as a functional ingredient for nutritional enrichment of cereal products (Sójka et al., 2013; Adamczyk et al., 2025). The presence of dietary fiber in both CF and CP may also influence dough properties through competition with gluten proteins for available water (Littardi et al., 2020).

Energy value increased progressively from WF (354.15 kcal/100 g) to CF (364.76 kcal/100 g) and CP (375.51 kcal/100 g), driven by the higher lipid and carbohydrate contents of the alternative ingredients, a trend previously reported in plant-enriched cereal systems (Brochard et al., 2021). Replacing WF with increasing levels of CF drove clear and consistent compositional shifts across Set I formulations.

Moisture decreased gradually from 12.24% (PCF0) to 11.75% (PCF30), likely reflecting the lower water retention capacity of non-gluten materials (Altıner & Mete, 2020). Protein content dropped from 9.68% to 9.09% as gluten-forming proteins were progressively diluted, a reduction of 0.5-1.5% typical of chestnut-enriched cereal products (Dziki, 2021; Alinovi et al., 2023), which may weaken the gluten network and affect dough structure (Littardi et al., 2020). Fat rose from 1.22% to 2.02%, ash increased markedly from 0.55% to 1.31%, and dietary fiber climbed from 2.58% to 3.94%, together reflecting the mineral- and fiber-rich character of CF (Ciucure et al., 2022; Alinovi et al., 2023). Energy value increased slightly (354.94-357.87 kcal/100 g), mainly driven by the higher lipid fraction of CF (Brochard et al., 2021). CF incorporation produced a gradual dilution of structural proteins accompanied by

meaningful enrichment in fiber, lipids, and minerals, supporting its use as a functional cereal ingredient (Altıner & Mete, 2020; Pop et al., 2025). Adding CP to the PCF20 base matrix brought more targeted changes. Moisture decreased slightly (11.91-11.65%) and protein showed only minor reductions (9.28-9.11%), indicating that chokeberry fortification has limited impact on the macronutrient backbone of the formulation, a pattern typical of berry-enriched cereal products (Dziki, 2021; Adamczyk et al., 2025). The most pronounced effect was on dietary fiber, which rose from 3.49% to 4.28%, and ash, which increased from 1.05% to 1.24%, reflecting the concentrated fiber and mineral content of CP (Sójka et al., 2013; Zbikowska et al., 2024). Fat increased slightly (1.75-1.92%), consistent with the lipid fraction of berry seeds (Brochard et al., 2021), and energy value remained nearly stable (356.89-358.03 kcal/100 g). CP delivered stronger fiber and mineral enrichment at lower substitution levels, without the protein dilution effect associated with CF. This complementary behavior makes the combined use of chestnut flour and chokeberry powder a balanced strategy for developing multifunctional cereal products with enhanced nutritional profiles (Sady & Sielicka-Różyńska, 2019; Zbikowska et al., 2024; Zeng et al., 2024; Adamczyk et al., 2025; Stoin et al., 2025).

Cooking quality of pasta formulations

The cooking quality parameters of the pasta samples are presented in Table 3. All cooking quality parameters differed significantly ($p < 0.05$) among Set I formulations, as indicated by different superscript letters in Table 3, while in Set II, the swelling index showed no significant differences among samples. Replacing WF with CF had a clear and progressive impact on all four cooking parameters. OCT dropped from 9.03 min (PCF0) to 7.10 min (PCF30), pointing to faster hydration and starch gelatinization as the gluten network became increasingly disrupted, a well-documented effect of non-gluten flour incorporation in pasta systems (Littardi et al., 2020; Alinovi et al., 2023). The reduction in cooking time may also be partly attributed to the lower protein content of CF, which reduces the resistance of the pasta structure to water penetration during thermal treatment. CL climbed from 3.54% to 4.27%, reflecting the reduced ability of the weakened protein matrix to retain soluble components during cooking (Dziki, 2021; Brochard et al., 2021). Although the CL values recorded remained within the acceptable range typically reported for enriched pasta products, the progressive increase with CF substitution level confirms that gluten dilution is the primary factor compromising structural integrity. WA rose sharply from 170.08 to 218.09 g/100 g dry pasta, driven by the higher fiber content of CF, since dietary fibers bind water and promote swelling during thermal processing (Altıner & Mete, 2020). The marked increase in WA also suggests that the composite pasta matrix became more porous and accessible to water as CF content increased, which is consistent with the simultaneous decrease in OCT. SI followed the same upward trend, increasing from 2.70 to 3.18, further supporting enhanced water uptake and structural expansion in chestnut-containing formulations (Alinovi et al., 2023).

The addition of CP to the PCF20 base produced more modest but consistent changes. OCT decreased slightly from 8.00 min (PCF20) to 7.04 min (PCF20CP6), suggesting that berry-derived particles may facilitate water diffusion within the pasta matrix (Sójka et al., 2013). This effect, though less pronounced than that of CF, indicates that even small amounts of chokeberry powder can influence the kinetics of water absorption during cooking. CL increased moderately from 4.05% to 4.48%, likely due to additional disruption of protein continuity by insoluble berry fibers (Mildner-Szkudlarz et al., 2009). WA continued to rise, reaching 216.88 g/100 g dry pasta at the highest CP level, while SI remained statistically stable across all Set II samples (3.08-3.17), indicating that CP enhances hydration capacity without substantially altering structural expansion, a behavior attributed to the water-binding properties of berry cell wall polysaccharides (Adamczyk et al., 2025). The stability of SI in Set II, despite increasing WA values, suggests that the berry-derived components promote uniform water distribution within the matrix rather than driving overall structural loosening.

Considering both sets together, protein dilution emerged as the primary driver of structural changes and cooking loss, while fiber enrichment governed hydration behavior.

Table 3. Cooking properties of pasta

Samples	Cooking properties of pasta			
	OCT (min)	CL (%)	WA (g/100 g dry pasta)	SI
Pasta formulations (Set I)				
PCF0	9.03±0.20^{a}	3.54±0.04^{d}	170.08±0.22^{d}	2.70±0.04^{d}
PCF10	8.08±0.11^{b}	3.88±0.03^{c}	192.46±0.24^{c}	2.92±0.03^{c}
PCF20	8.00±0.12^{b}	4.05±0.05^{b}	208.28±0.21^{b}	3.08±0.07^{b}
PCF30	7.10±0.13^{c}	4.27±0.07^{a}	218.09±0.25^{a}	3.18±0.02^{a}
Pasta formulations (Set II)				
PCF20	8.00±0.12^{a}	4.05±0.05^{d}	208.28±0.21^{d}	3.08±0.07^{a}
PCF20CP2	7.13±0.10^{b}	4.18±0.04^{c}	211.25±0.23^{c}	3.11±0.06^{a}
PCF20CP4	7.08±0.12^{b}	4.32±0.05^{b}	214.66±0.19^{b}	3.15±0.05^{a}
PCF20CP6	7.04±0.14^{b}	4.48±0.06^{a}	216.88±0.26^{a}	3.17±0.02^{a}

WF - Wheat flour; CF - chestnut flour; CP: chokeberry powder**;** PCF0 - Control pasta (100% wheat flour (WF): 0% chestnut flour (CF); PCF10 - Pasta sample with 90% wheat flour (WF): 10% chestnut flour (CF); PCF20 - Pasta sample with 80% wheat flour (WF): 20% chestnut flour (CF); PCF30 - Pasta sample with 70% wheat flour (WF): 30% chestnut flour (CF); PCF20CP2 - Pasta sample with 78% wheat flour (WF): 20% chestnut flour (CF): 2% chokeberry powder (CP); PCF20CP4 - Pasta sample with 76% wheat flour (WF): 20% chestnut flour (CF): 4% chokeberry powder (CP); PCF20CP6 - Pasta sample with 74% wheat flour (WF): 20% chestnut flour (CF): 6% chokeberry powder (CP). *CRB - carbohydrates. Data are presented as mean ± standard deviation of three independent analyses. Values with different letters within the same column are significantly different (one-way ANOVA, $p < 0.05$), while those with the same letter are not significantly different ($p > 0.05$).

Considering both sets together, protein dilution emerged as the primary driver of structural changes and cooking loss, while fiber enrichment governed hydration behavior. CF, acting through gluten dilution, produced stronger shifts in cooking parameters, whereas CP contributed additional hydration and minor structural effects. The magnitude of change was directly proportional to the compositional modifications described in the proximate analysis, supporting the view that technological performance in composite pasta is largely determined by the balance between gluten-forming proteins and non-gluten components (Dziki, 2021; Brochard et al., 2021).

Phytochemical profile of pasta formulations

The phytochemical profile of the raw materials and pasta formulations, expressed as total phenolic content (TPC) and antioxidant activity (DPPH, µmol TE/g d.w.), is presented in Table 4. All phytochemical parameters differed significantly ($p < 0.05$) among samples, as indicated by different superscript letters in Table 4. The three raw materials differed substantially in their phytochemical profiles, highlighting the central role of the enrichment ingredients in driving the functional potential of the final products. WF showed low TPC (52.64 mg GAE/100 g d.w.) and antioxidant activity (2.96 µmol TE/g d.w.), which is expected for refined wheat matrices, where phenolic depletion during milling substantially reduces radical-scavenging capacity (Shahidi & Ambigaipalan, 2015; Dziki, 2021). CF reached moderately higher phytochemical levels (186.36 mg GAE/100 g d.w.; 28.82 µmol TE/g d.w.), consistent with reported ranges of 150-300 mg GAE/100 g for chestnut-derived ingredients, with variation attributed to cultivar and processing conditions (Ciucure et al., 2022; Alinovi et al., 2023).

Table 4. Phytochemical profile of pasta formulations

Samples	Phytochemical Parameters	
	Total phenolic compounds (mg GAE / 100g d.w.)	Antioxidant activity (µmol TE/g d.w.)
Raw materials		
WF	52.64±0.36^{e}	2.96±0.12^{e}
CF	186.36±1.22^{b}	28.82±0.13^{b}
CP	5390.66±0.24^{a}	860.44±0.16^{a}
Pasta formulations (Set I)		
PCF0	26.84±0.20^{d}	1.68±0.14^{d}
PCF10	34.78±0.33^{c}	3.04±0.12^{c}
PCF20	45.02±0.44^{b}	4.36±0.11^{b}
PCF30	52.89±0.26^{a}	5.89±0.15^{a}
Pasta formulations (Set II)		
PCF20	45.02±0.44^{d}	4.36±0.11^{d}
PCF20CP2	145.86±0.32^{c}	20.87±0.16^{c}
PCF20CP4	178.66±0.26^{b}	35.66±0.18^{b}
PCF20CP6	198.44±0.11^{a}	52.44±0.20^{a}

WF - Wheat flour; CF - chestnut flour; CP: chokeberry powder**;** PCF0 - Control pasta (100% wheat flour (WF): 0% chestnut flour (CF); PCF10 – Pasta sample with 90% wheat flour (WF): 10% chestnut flour (CF); PCF20 - Pasta sample with 80% wheat flour (WF): 20% chestnut flour (CF); PCF30 - Pasta sample with 70% wheat flour (WF): 30% chestnut flour (CF); PCF20CP2 - Pasta sample with 78% wheat flour (WF): 20% chestnut flour (CF): 2% chokeberry powder (CP); PCF20CP4 - Pasta sample with 76% wheat flour (WF): 20% chestnut flour (CF): 4% chokeberry powder (CP); PCF20CP6 - Pasta sample with 74% wheat flour (WF): 20% chestnut flour (CF): 6% chokeberry powder (CP). *CRB - carbohydrates. Data are presented as mean ± standard deviation of three independent analyses. Values with different letters within the same column are significantly different (one-way ANOVA, $p < 0.05$), while those with the same letter are not significantly different ($p > 0.05$).

CP stood out with exceptionally high phytochemical density (5390.66 mg GAE/100 g d.w.; 860.44 µmol TE/g d.w.), placing it within the wide range documented for aronia-derived products (2000-8000 mg GAE/100 g d.w.) and

reinforcing its status as one of the most antioxidant-rich berry ingredients available (Kulling & Rawel, 2008; Sójka et al., 2013; Jakobek et al., 2025). A notable observation concerns the control pasta (PCF0: 26.84 mg GAE/100 g d.w.), whose TPC was considerably lower than that of WF (52.64 mg GAE/100 g d.w.). This reduction suggests that the pasta manufacturing process, including extrusion and drying, induces partial degradation of phenolic compounds, a phenomenon previously documented in functional pasta systems (Melini et al., 2020; Bresciani et al., 2022). In Set I formulations, replacing WF with increasing levels of CF led to a steady rise in both TPC and antioxidant activity, with TPC growing from 26.84 mg GAE/100 g d.w. (PCF0) to 52.89 mg GAE/100 g d.w. (PCF30) and antioxidant activity climbing from 1.68 to 5.89 µmol TE/g d.w. This roughly two-fold gain in TPC agrees with the 1.5-2.5-fold increases reported in chestnut-enriched cereal products (Littardi et al., 2020; Alinovi et al., 2023). While the absolute values remain modest relative to berry-enriched systems, the trend is fully consistent with the moderate but reliable phytochemical contribution of chestnut flour in composite matrices (Dziki, 2021). In Set II, even small additions of CP triggered a steep rise in both parameters. TPC climbed from 45.02 mg GAE/100 g d.w. (PCF20) to 198.44 mg GAE/100 g d.w. (PCF20CP6), while antioxidant activity jumped from 4.36 to 52.44 µmol TE/g d.w., a more than ten-fold increase. This response reflects the extraordinary phenolic richness of chokeberry and is well supported by studies showing that berry powders can elevate the phenolic content of cereal matrices by 2–5 times depending on inclusion level (Mildner-Szkudlarz et al., 2009; Jakobek et al., 2025; Stoin et al., 2025). Comparable gains in antioxidant capacity have been reported in berry-fortified pasta and bakery products, where anthocyanin-rich ingredients play a dominant role in enhancing radical-scavenging activity (Shahidi & Ambigaipalan, 2015). Throughout all formulations, TPC and DPPH values increased in parallel, reflecting the well-known link between phenolic concentration and antioxidant capacity in plant-based foods, with correlations above $r > 0.8$ consistently reported in cereal-berry composite systems (Shahidi & Ambigaipalan, 2015; Brochard et al., 2021). These results position CF as a moderate phytochemical enhancer and CP as a high-impact functional ingredient capable of substantially elevating the antioxidant profile of pasta formulations, a pattern consistent with recent findings on cereal products fortified with berry-derived bioactive ingredients (Mildner-Szkudlarz et al., 2009; Pop et al., 2025; Stoin et al., 2025).

Changes in the cooking time of pasta formulations

As shown in Table 5, optimal cooking time (OCT) differed significantly ($p < 0.05$) among pasta formulations at each storage interval, indicating that ingredient composition influenced the cooking behavior of the samples. Optimal cooking time is defined as the time required for complete starch gelatinization and disappearance of the uncooked core and is commonly used as an indicator of pasta cooking quality (Littardi et al., 2020).

Table 5. Changes in the cooking time of pasta formulations

Samples	Storage days		
	0	30	60
Pasta formulations (Set I)			
PCF0	9.03±0.20^{a}	8.90±0.10^{a}	8.40±0.21^{a}
PCF10	8.08±0.11^{b}	8.00±0.14^{b}	7.50±0.24^{b}
PCF20	8.00±0.12^{b}	7.90±0.11^{c}	7.40±0.21^{c}
PCF30	7.10±0.13^{c}	7.00±0.15^{d}	6.50±0.25^{d}
Pasta formulations (Set II)			
PCF20	8.00±0.12^{a}	7.90±0.11^{a}	7.40±0.21^{a}
PCF20CP2	7.13±0.10^{b}	7.00±0.12^{b}	6.40±0.12^{b}
PCF20CP4	7.08±0.12^{b}	6.95±0.15^{b}	6.25±0.15^{b}
PCF20CP6	7.04±0.14^{b}	6·90±0.14^{b}	6·10±0.14^{b}

WF - Wheat flour; CF - chestnut flour; CP: chokeberry powder; PCF0 - Control pasta (100% wheat flour (WF): 0% chestnut flour (CF); PCF10 - Pasta sample with 90% wheat flour (WF): 10% chestnut flour (CF); PCF20 - Pasta sample with 80% wheat flour (WF): 20% chestnut flour (CF); PCF30 - Pasta sample with 70% wheat flour (WF): 30% chestnut flour (CF); PCF20CP2 - Pasta sample with 78% wheat flour (WF): 20% chestnut flour (CF): 2% chokeberry powder (CP); PCF20CP4 - Pasta sample with 76% wheat flour (WF): 20% chestnut flour (CF): 4% chokeberry powder (CP); PCF20CP6 - Pasta sample with 74% wheat flour (WF): 20% chestnut flour (CF): 6% chokeberry powder (CP). *CRB - carbohydrates. Data are presented as mean ± standard deviation of three independent analyses. Values with different letters within the same column are significantly different (one-way ANOVA, $p < 0.05$), while those with the same letter

At day 0, the control sample (PCF0) showed the longest cooking time (9.03 min), significantly higher ($p < 0.05$) than all composite formulations. Progressive substitution of wheat

flour (WF) with chestnut flour (CF) reduced OCT to 8.08 min (PCF10), 8.00 min (PCF20), and 7.10 min (PCF30). This reduction suggests that the presence of chestnut flour facilitates water penetration and heat transfer during cooking, likely due to partial weakening of the gluten network (Alinovi et al., 2023). In Set II, the incorporation of chokeberry powder (CP) into the PCF20 formulation further reduced OCT, with values ranging from 7.13 min (PCF20CP2) to 7.04 min (PCF20CP6). Although differences among chokeberry-enriched samples were not statistically significant, OCT values remained lower than those of the PCF20 reference. This suggests that berry-derived fiber may facilitate water diffusion within the pasta matrix (Mildner-Szkudlarz et al., 2009; Foschia et al., 2013; Biernacka et al., 2019). During storage, a slight decrease in OCT was observed across all formulations while maintaining the same ranking among samples. After 60 days, the control sample decreased to 8.40 min, whereas CF-enriched samples reached values as low as 6.50 min (PCF30). In Set II, the lowest OCT was recorded for PCF20CP6 (6.10 min). Similar reductions in cooking time during storage have been reported for pasta formulated with alternative flours, where structural relaxation and moisture redistribution may occur over time (Vimercati et al., 2020; Dziki, 2021; Bresciani et al., 2022; Santos et al., 2025).

CONCLUSIONS

This study confirms that the combined use of CF and CP is an effective approach to improve the nutritional and functional profile of enriched pasta while maintaining acceptable technological quality. CF addition mainly increased dietary fiber and mineral content and induced moderate changes in cooking behavior associated with partial weakening of the gluten matrix. In contrast, CP exerted a stronger functional effect, significantly enhancing phenolic content and antioxidant capacity even at low inclusion levels. Despite these compositional changes, the enriched formulations retained satisfactory cooking performance, indicating that functional fortification can be achieved without major structural deterioration. The complementary roles of CF and CP enabled the development of pasta with improved nutritional value, enhanced bioactive potential, and balanced technological characteristics. Among the evaluated samples, PCF20CP4 showed the most favorable overall profile, providing the best compromise between improved nutritional value, elevated antioxidant activity, and acceptable cooking properties. These findings support the use of CF and CP as synergistic ingredients in the formulation of value-added cereal-based products. Overall, the results contribute to a better understanding of how ingredient interactions influence quality attributes in composite pasta systems and provide a solid basis for the development of functional cereal products with enhanced health-related potential.

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