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Physicochemical and nutritional quality of pigmented rice and bran: Influence of milling and cooking

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ABSTRACT

Pigmented rice bran is under-researched for human nutrition. This study investigated milling and cooking effects on the physicochemical and nutritional quality of pigmented and non-pigmented rice. Raw rice properties, cooking behavior and nutritional *in-vitro* quality were evaluated. Samples were cooked following a "risotto" preparation method. Bran removal by milling reduced kernel dimension (15%) and hardness (8%). Pigmented rice had higher total phenolic content (TPC; >41%) and higher antioxidant activity (AOA; >24%) than Carnaroli but milling significantly ($p \leq 0.05$) reduced them. The bran was fractionated and (re)added during rice cooking as a new strategy to preserve nutritional compounds at their best. Compared with brown rice, milled samples exhibited greater geometric expansion and shorter cooking times (>47%), confirming that removal of the outer layer facilitated water penetration. Cooking affected the TPC differently depending on the rice variety (e.g., -15.5% for Violet and +7.8% for Orange brown samples). The incorporation of rice bran during cooking improved the "risotto" color and its nutritional value (TPC > 53% and AOA > 60%). Results evidenced the impact of different processing methods on rice quality, suggesting the potential use of rice co-product (i.e., bran) as new ingredient for healthier and more sustainable foods.

1. Introduction

Rice (*Oryza sativa* L.) is one of the most important energy sources worldwide (Fracassetti, Pozzoli, Vitalini, Tirelli, & Iriti, 2020) and one of the most economically important cereal crop species in Italy, the first rice producer in the European Union (Russo & Callegarin, 2007).

After the rice harvest, plants are dehulled to obtain brown rice, which can be further milled. Abrasive milling separates outer layers, producing milled, polished or white rice and, as co-products, bran and polish (Juliano & Tuaño, 2019). Rice grains are generally consumed as white rice (Bhat et al., 2020). However, the processes of dehulling and milling discards nutritional and nutraceutical compounds like fibers (20.5%–33.3%), starch (16.1%–26.7%), ash (9.2%–13.9%), proteins (13.2%–18.6%), lipids (9.5%–22.9%), vitamins, tocopherols, tocotrienols, oryzanols and other phenolics (Bordiga et al., 2014; Liu, Zhang, Yi, Quan, & Lin, 2021). Bran is one of the most abundant co-products traditionally used in animal feed, though little used in human nutrition even if some studies highlight the nutritional benefits of rice bran (Chen et al., 2023; Manzoor et al., 2023). For this reason and owing to growing consumer interest in health-promoting foods, increasing attention has been paid to pigmented (Mbanjo et al., 2020) rice varieties (Mestres, Briffaz, & Valentin, 2019), commercialized as brown rice or processed through parboiling and milling. Pigmented rice grains, characterized by red, black or purple pericarps, are rich in phenolic

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Abbreviations: a*, red index; AOA, antioxidant activity; AOAC, Association of Official Agricultural Chemists; b*, blue index; B, brown; BC, brown Carnaroli rice; BO, brown Orange rice; Br, bran; BrC, Carnaroli bran; BrO, Orange bran; BrV, Violet bran; BV, brown Violet rice; C, Carnaroli; CPVO, Community Plant Variety Office; CY, cyanidin-3-*O*-glucoside; d.m., dry matter; DPI, dot per inch; DPPH, 1,1-diphenyl-2-picrylhydrazyl; GA, gallic acid; GAE, gallic acid equivalents; L*, lightness; M, milled; MC, milled Carnaroli; MCBrC, milled Carnaroli rice with Carnaroli bran; MCBrO, milled Carnaroli rice with Orange bran; MCBrV, milled Carnaroli rice with Violet bran; MO, milled Orange rice; MOBrO, milled Orange rice with Orange bran; MV, milled Violet rice; MVBrV, milled Violet rice with Violet bran; O, Orange; TA, total anthocyanin content; TPC, total phenolic content; V, Violet; WBC, water binding capacity; WI, weight increase.

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compounds, including flavonoids (anthocyanins, proanthocyanidins, flavonols and flavan-3-ols) and phenolic acids (Bordiga et al., 2014; Delgado-Vargas, Jiménez, Paredes-López, & Francis, 2000; Finocchiaro, Ferrari, & Gianinetti, 2010; Fracassetti et al., 2020; Renger & Steinhart, 2000; Zaupa, Calani, Del Rio, Brighenti, & Pellegrini, 2015).

Dark purple rice has been found to be the richest cultivar for anthocyanins, while red varieties contain mainly proanthocyanidins. These phenolic compounds have received great attention due to their potential beneficial effects in terms of oxygen free radical scavenging activity (Bordiga et al., 2014; Bordiga, Travaglia, Locatelli, Coïsson, & Arlorio, 2011; Finocchiaro et al., 2010; Irakli, Samanidou, Katsantonis, Biliaderis, & Papadoyannis, 2016). This is because oxidative stress is considered a key factor in the development of chronic diseases (Bordiga et al., 2011), including cardiovascular diseases (Ling, Cheng, Ma, & Wang, 2001; Ling, Wang, & Ma, 2002), diabetes (Boue, Daigle, Chen, Cao, & Heiman, 2016) and celiac disease. In celiac disease, although a strict gluten-free diet generally reduces inflammation and intestine damage, several studies have reported a persistent oxidative status despite the adherence to the diet. Pigmented rice, abundant in phenolic compounds with recognized antioxidant activity, has been suggested as a potential nutriment to counteract this condition (Rowicka et al., 2018). One of the most critical aspects of flavonoids and other antioxidants in rice is their stability during post-harvest processes (storage conditions, drying and packaging) (Ito & Lacerda, 2019; Norkaew et al., 2017) and thermal treatments (Colasanto et al., 2021), included the cooking process necessary to make rice edible. Furthermore, cooking can lead to a loss of antioxidant activity, although the "risotto" preparation preserves these compounds and related antioxidant activity (Colasanto et al., 2021; Finocchiaro et al., 2010) better than boiling because it minimizes the loss of water-soluble compounds. In "risotto", a typical Italian preparation, a small amount of water or broth is gradually added to the rice during cooking. Rice absorbs the liquid and expands while reducing its consistency and partially releasing starch. Cooking continues until most of the liquid is completely absorbed (Melini, Panfili, Fratianni, & Acquistucci, 2019), and a limited amount of the water-solution remains, producing a "creamy risotto".

Traditionally, compared to brown rice consumers prefer polished rice with little or no bran due to its characteristic shorter cooking time (Colombo et al., 2023; Gyawali et al., 2022; Lyon et al., 1999; Mestres et al., 2019). However, pigmented rice, which is less commonly subjected to extensive milling (Zhang et al., 2024), is gaining popularity. This trend can be attributed to the growing awareness of the nutritional and nutraceutical benefits associated with pigmented rice varieties (Bani, Di Lorenzo, Restani, Mercogliano & Colombo., 2023; Colombo et al., 2023). However, pigmented rice bran is susceptible to oxidation due to its lipid content (Juliano et al., 2019), which can reduce its shelf life. Additionally, incorporating pigmented rice bran into industrial food products present technical challenges due to the bran's interaction with other ingredients (Gul, Yousuf, Singh, Singh, & Wani, 2015). For instance, literature studies (Park, Kim, & Kim, 2001; Shobana et al., 2011) indicate that increasing the degree of polishing decreases the chewiness of rice, possibly due to the reduction of its bran constituents. Furthermore, the flavor and distinct color of pigmented rice bran can affect the sensory perception of food products, as already happens with pigmented rice (Cappa et al., 2021). Therefore, to meet consumer demand for foods with beneficial nutritional, nutraceutical and sensory properties, different processing strategies need to be investigated.

The aim of this study was to evaluate the impact of milling and cooking on the physicochemical and nutritional quality of pigmented and non-pigmented rice varieties, particularly regarding the content of free phenolic compounds. Brown and partially milled rice were cooked using the "risotto" method, to highlight the impact of the hydrothermal process on the physicochemical characteristics of the different rice varieties. The bran, derived from the milling process, was collected, fractionated, characterized, and added to milled samples during cooking to explore a new healthy and readily available rice co-product, that has been under-researched for human nutrition until now. The findings of this study might prove valuable to food companies that could benefit from rice milling co-products, promoting innovation and the production of healthy foods. Furthermore, consumers could benefit from new products with shorter cooking times and interesting physical and chemical properties, such as the quantity and bioactivity of antioxidant compounds.

2. Materials and methods

2.1. Chemicals

Methanol (CAS number: 67-56-1), ethanol (CAS number: 64-17-5), HPLC grade water (CAS number: 7732-18-5), Folin-Ciocalteu reagent (CAS number: 31360.264) and 1 mol/L HCl (CAS number: 7647-01-0) were obtained from VWR International (Fontenay-sous-Bois, France). 1,1-diphenyl-2-picrylhydrazyl (DPPH) (CAS number: 107-75-1), gallic acid standard (CAS number: 5995-86-8) were purchased from Sigma Aldrich (Steinheim, Germany).

2.2. Rice and bran samples

The samples evaluated are listed in Table 1 and Fig. 1. All samples were provided by "Azienda Agricola Bertolone Eleonora di Bertolone Giovanni" (Collobiano, VC, Italy). The two pigmented rice samples were grown in Piedmont (Italy) and are registered at the Community Plant Variety Office (CPVO). In particular, the pigmented samples considered were Violet (V) rice (medium-grain rice, black variety – patent no. 46269/2017) (CPVO, 2017b) and Orange (O) rice (medium-grain rice, red variety – patent no. 46270/2017) (CPVO, 2017a). Brown (B) samples were kernels that are retained within the hull (i.e., not milled), while partially milled (M) samples were brown rice polished at an industrial plant (Azienda Agricola Bertolone Eleonora di Bertolone Giovanni", Collobiano, VC, Italy) following an internal standard procedure to reach 7–10% degrees of milling. During milling, bran (Br) was collected and then manually sieved in the laboratory to remove particles

Table 1
Cooking conditions and sample codes used for different rice samples.

Sample		Code	Ratio rice (g)/water (mL)[a]	Bran addition[a] (g)	Cooking time (min)
Violet (V)	brown (B)	BV	50/275	–	41
	milled (M)	MV	50/190	–	17
	milled + bran (Br) Violet	MVBrV	50/220	5	17
Orange (O)	brown (B)	BO	50/250	–	35
	milled (M)	MO	50/170	–	14
	milled + bran (Br) Orange	MOBrO	50/190	5	14
Carnaroli (C)	brown (B)	BC	50/240	–	34
	milled (M)	MC	50/180	–	18
	milled + bran (Br) Carnaroli	MCBrC	50/210	5	18

[a] Water was added in multiple steps; bran was added 5 min before the end of cooking.

Fig. 1. Rice kernels were treated differently (brown, milled or milled + bran) before (raw) and after cooking. From top to bottom, Violet, Orange and Carnaroli samples.

bigger than 500 μm, which were discarded. For comparison, Carnaroli (C) rice (medium-grain rice, non-pigmented) commonly used for "risotto" preparation was analyzed. According to label information, brown Violet (BV) rice provides 1461 kJ per 100 g, with 3.3 g of total fat including 0.8 g of saturated fat; It contains 68.3 g of total carbohydrates with 1.1 g of sugars, 3.9 g of fiber, and 8.7 g of protein. Brown Orange (BO) rice has 1455 kJ of energy per 100 g, with 2.9 g of total fat including 0.8 g of saturated fat, and 69.8 g of total carbohydrates with 1.2 g of sugars; It also provide 3.8 g of fiber and 7.6 g of protein. Milled Carnaroli (MC) rice provides 1506 kJ of energy per 100 g, with 2.1 g of total fat including 0.6 g of saturated fat, and 76.5 g of total carbohydrates with 0.7 g of sugars; It also contains 1.1 g of fiber and 6.8 g of protein. All samples, already processed as defined by the study, were stored under vacuum in the dark at 4 °C until analysis.

2.3. Cooking protocol

Preliminary tests determined the rice-to-water ratio and cooking time. Brown and milled samples were cooked in an induction pan (diameter 24 cm, height 5.5 cm) following the "risotto" cooking method summarized in Table 1 by adding a limited amount of water in subsequent steps: 150 g at the beginning of cooking, 20–50 g after approximately 10 min and the remaining water after 14–25 min according to the total cooking time. Bran powder was added to the milled rice 5 min before the end of cooking to preserve thermolabile compounds. All cooking experiments (Fig. 1) were performed in duplicate using an induction heater (Severini, Germany) set to high power level (i.e., 10) for 1.5 min, then reduced to minimum power (i.e., 1) for the remaining cooking time.

2.4. Physicochemical characterization

2.4.1. Color evaluation

The color indices of the rice samples (raw and cooked) were evaluated after they were evenly spread onto a Petri dish (25 mm diameter) using a colorimeter (Chroma Meter II Reflectance, Minolta, Osaka, Japan), whose head (tip of the head was 8 mm in diameter) was applied directly to the sample surface at five different stellar points (Cappa et al., 2021; Colombo et al., 2023). The illumination system consisted of a high-power pulsed xenon arc lamp using C-illuminant. The colorimeter was calibrated using a standard white reflector plate (Y = 87.7; x = 0.308; y = 0.315). The results are expressed in the CIE L*a*b* space as L* (lightness; from black (0) to white (100)), a* (from green (−) to red (+)), and b* (from blue (−) to yellow (+)) values. To quantify the effect of cooking and bran addition, ΔE values were calculated for cooked brown and milled samples compared to raw samples and for cooked milled samples with added bran compared to cooked milled samples, using the following equation:

$$\Delta E = \sqrt{\Delta L^2 + \Delta a^2 + \Delta b^2}$$

2.4.2. Particle size distribution and water binding capacity

Bran particle size distribution was evaluated using five sieves with mesh sizes of 90–125–250–500 μm and 1 mm. An automatic sieve (Octagon Digital, Endecotts, London, England) was used for this purpose, and three balls were placed on the layer with a larger mesh size to facilitate sieving. Bran (50 g) was sifted for 10 min with an oscillation amplitude of 9. The retentate of each sieve was measured gravimetrically, compared to the initial weight, and multiplied by one hundred to obtain the percentage distribution of each fraction. After sieving, all the fractions ≤500 μm were combined and characterized in terms of moisture (g/100 g; gravimetrically at 105 °C down to constant weight) and color (as previously reported), together with the water binding capacity (WBC). For WBCs, 0.5 g of fractioned bran was mixed with 50 mL of distilled water, kept at room temperature for 1 h, and stirred manually every 10 min. The excess water was removed by centrifugation (Lisa Centrifuge 2 L Refrigerated, AFI, France) at 25 °C for 10 min at 2200×*g*. The water amount retained by the sample was calculated using the following equation:

$$WBC\ (g/g, wet\ basis) = \frac{w_f - w_i}{w_i}$$

where w_f is the final weight and w_i is the initial weight.

2.4.3. Dimension of rice kernel

According to previous studies in which the geometrical dimensions of rice samples (Mariotti, Fongaro, & Catenacci, 2010) and 25 bean seed varieties (Cappa, Kelly, & Ng, 2018) were evaluated via image analysis, the images of randomly picked rice kernels of each variety were scanned at 24 bit and at a resolution of 300 dpi using an Epson Perfection V850pro scanner (Seiko Epson Corporation, Japan); scans were saved in TIFF format. Kernels were scanned before and after cooking to investigate the effect of hydrothermal treatment on rice dimensions. Images were processed using dedicated software (Image-Pro Plus 4.5.1.29/XP; Media Cybernetics, Inc., Rockville, MD, USA), measuring length (mm; major axis), width (mm; minor axis) and area (mm^2). The average measurements of 50 kernels for each sample were used to calculate the percentage increase in length, width and area compared to the original dimensions (i.e., raw samples).

2.4.4. *Weight increase*

The weight increase (WI, %) during cooking was evaluated by weighing rice before and after cooking. WI was determined as the increase in cooked rice weight relative to the raw kernel weight. The results were the average of at least 2 replicates per cooking of approximately 50 g of sample for time.

2.4.5. *Textural properties*

Raw and cooked rice kernel texture values were measured using a texture analyzer TA.HDPlus (Stable Micro Systems, Surrey, UK) equipped with a plate probe (45 mm in diameter) and a 500-N load cell. As temperature affects textural properties, cooked samples were cooled in an airtight container to prevent sample dehydration for 20 min at room temperature (22 ± 2 °C) before texture evaluation. Texture Exponent TEE32 V 3.0.4.0 software (Stable Micro System, Surrey, UK) was used to control the instrument and for data acquisition. Five kernels positioned in a stellar configuration under the probe were compressed to 80% strain at a speed of 0.2 mm/s. The maximum force (N) registered was extrapolated from the stress–deformation curve as an index of the product hardness. Fifteen measurements were carried out for each sample.

2.5. *Nutritional evaluation*

2.5.1. *Sample preparation*

About 50 g of raw rice was ground into powder at 25 °C using a disc mill (MLI 204, Buhler, Italy) following a standardized procedure (Colombo et al., 2023). In accordance with Bhatta, Stevanovic Janezic, and Ratti (2020), to preserve the polyphenols at their best, the rice powders were immediately freeze-dried (Modulyo, Edwards vacuum, Italy) and then maintained at −20 °C until analysis. For the same reason, the cooked samples were freeze-dried (Modulyo, Edwards vacuum, Italy), ground using a coffee mill and maintained at −20 °C until analysis.

2.5.2. *Characterization of the anthocyanin profile*

Freeze-dried Violet sample (0.5 g; raw or cooked) was mixed with 10 mL of methanol:1 mol/L HCl 85:15 (v/v) (Colombo et al., 2023; Shipp & Abdel-Aal, 2010). Samples were extracted for 30 min at room temperature (22 ± 2 °C) in the dark and centrifuged at 8000×*g* for 20 min at 4 °C (Avanti J-25, Beckman Coulter, Brea, CA, USA). Extracted solutions were filtered using a 0.45 μm filter (VWR International, Fontenay-sous-Boys, France) and stored at −20 °C until analysis. The extraction procedure was repeated three times.

Total anthocyanin (TA) content was determined according to the AOAC method (AOAC International, 2006): rice extracts were diluted with KCl buffer (0.025 mol/L, pH 1) and CH_3COONa buffer (0.4 mol/L, pH 4.5). After 20 min, the absorbance was measured at 520 nm and 700 nm (to correct for haze) using a UV–Vis spectrophotometer (Varian Cary 50 SCAN, Palo Alto, CA, USA). TA content was expressed as equivalents of cyanidin-3-*O*-glucoside (mg CY/g dry matter (d.m.)) (Sharma, Dash, & Badwaik, 2022a):

$$\text{TA (mg CY/g)} = \Delta A \times MW \times DF \times 1000 \times V/e \times l \times W$$

where: $\Delta A = (A_{520nm} - A_{700nm})$ pH 1.0 - $(A_{520nm} - A_{700nm})$ pH 4.5; MW: molecular weight (449.2 g/mol for CY); DF: dilution factor; 1000: conversion factor from g to mg; V: extraction volume (L); e: molar extinction coefficient (26,900 for CY); l: path length in cm (1 cm); and W: sample weight (g).

2.5.3. *Characterization of soluble phenolic compounds and antioxidant capacity*

Soluble phenolics were extracted using a 60:40 (v/v) ethanol:water solution following Catena et al. (2019) method. Portions of 0.5 g of freeze-dried flour or cooked sample were suspended in 10 mL of the hydro-alcoholic solution, stirred for 2 h at room temperature (22 ± 2 °C) in the dark, and centrifuged at 2000×*g* for 15 min at 4 °C (5810-R, Eppendorf, Hamburg, Germany). The supernatants were filtered using a 0.45 μm filter (VWR International, Fontenay-sous-Boys, France) and stored at −20 °C until analysis. Each sample was extracted three times.

The total phenolic content (TPC) was determined by applying Folin-Ciocalteu's assay (Singleton & Rossi, 1965): 300 μL of the samples (raw and cooked) or water (blank) were mixed with 1.5 mL of 0.2 mol/L Folin–Ciocalteu's reagent and 1.2 mL of 7.5 g/100 mL sodium carbonate. Absorbance was measured at 765 nm after 30 min; results were expressed as mg of gallic acid equivalents (GAE)/g d.m. using a calibration curve within a concentration range of 5–50 μg/mL.

Antioxidant activity (AOA) was evaluated using DPPH spectrophotometric assay (Brand-Williams, Cuvelier, & Berset, 1995). Volumes of 0.5 mL of rice extracts (raw and cooked) or water (blank) were mixed with 1 mL of 5 mg DPPH/100 mL in methanol. After 30 min in the dark, the absorbance was recorded at 517 nm against methanol. AOA was calculated using gallic acid (GA) as a reference standard; results were expressed as mg of gallic acid equivalents (GAE)/g d.m. based on a calibration curve ranging from 1.0 to 5.0 μg/mL.

2.6. *Statistical analysis*

The results are expressed as the mean ± standard deviation ($n \geq 3$). The data were subjected to one-way analysis of variance (ANOVA) followed by the least significant difference (LSD) test to identify significant ($p \leq 0.05$) differences between samples. Correlations between variables were assessed by Pearson linear correlation. STATGRAPHIC_Plus (StatPoint, Inc., The Palins, VA, USA) software was used for statistical data analysis.

3. Results and discussion

3.1. *Bran characterization*

Bran yields were of 7% for Violet variety and of 10% for Orange and

Table 2
Particle size distribution of bran samples obtained from Violet (V), Orange (O) and Carnaroli (C) rice.

Code	Particle size distribution (%)				
	$x \leq 125$ μm	$125 < x \leq 250$ μm	$250 < x \leq 500$ μm	$500 < x \leq 1000$ μm	>1000 μm
BrV	5.81 ± 1.92^b	65.26 ± 1.27^c	11.41 ± 0.47^a	16.58 ± 0.23^b	0.27 ± 0.22^a
BrO	0.82 ± 0.71^a	40.01 ± 0.84^b	38.14 ± 0.73^b	18.73 ± 0.46^c	0.60 ± 0.85^a
BrC	1.46 ± 0.58^a	28.06 ± 0.86^a	41.28 ± 1.68^c	12.42 ± 0.69^a	13.66 ± 0.36^b

Note: BrV, bran from Violet rice; BrO, bran from Orange rice; BrC, bran from Carnaroli rice; in the same column, values followed by different letters are significantly different ($p \leq 0.05$).

Carnaroli varieties, according to the abrasive procedure applied and previously discussed. Since particle size can affect water binding capacity (WBC) and consumer acceptability (Cappa et al., 2018; Cappa et al., 2021; Cappa, Kelly, & Ng, 2020), bran particle size distribution was evaluated (Table 2). Fractions bigger than 500 μm, mainly consisting of broken grains and tegumental parts, were discarded because they are quite big and can compromise consumer acceptability. Discarded fractions corresponded to 16.85% for BrV, 19.33% for BrO, and 26.08% for BrC; thus, the final yields of fractioned bran were: 5.8%, 8.1% and 7.4% for V, O and C, respectively. Their particle size distribution resulted as follows: BrV had 79% powder between 125 and 250 μm and 14% between 250 and 500 μm; BrO had 51% between 125 and 250 μm and 48% between 250 and 500 μm; and BrC had 40% between 125 and 250 μm, while 58% of the fraction was between 250 and 500 μm. As the process conditions were kept constant, differences among samples can be attributed to the intrinsic characteristics of the cereal plants, such as genetic diversity that determine grain shape, size and composition (Jiang, Zhang & Chen, 2022) and environmental factors which affect nutrient uptake and assimilation (Li et al., 2018).

All bran fractions equal or below 500 μm were combined and evaluated for colorimetric indices, moisture and WBC (Table 3), while their nutritional properties have already reported by Colombo et al. (2023); specifically, authors observed that the soluble polyphenol content ranges from 5.15 ± 0.68 to 40.17 ± 0.65 mg GAE/g. Additionally, the AOA measured by the DPPH assay showed values ranging from 1.21 ± 0.11 to 16.14 ± 0.12 mg GAE/g. As expected, the colorimetric indices of bran aligned with those of raw brown rice kernels ($r = 1$; $p < 0.05$). These findings are consistent with previous research showing bran contributes to the colorimetric characteristics observed in rice products (Chen et al., 2023; Gul et al., 2015). In our study the Orange sample exhibited the highest redness, the Carnaroli rice sample had the highest lightness value, and the Violet sample had the lowest L* and b* values. The moisture content was not significantly ($p > 0.05$) different among the samples ranging between 9.49 and 9.74 g/100 g. These values align with Petroni et al. (2017), who reported a moisture content of 9.11 g/100 g for a mixture of rice bran. Since bran was subsequently added to the rice during cooking, the WBC was determined to estimate the amount of water added to the rice. The data in Table 3 show that BrV had a significantly ($p \leq 0.05$) greater WBC than BrO and BrC, probably due to its smaller particle size. In fact, it is well known that the smaller the particle size, the greater the surface area and degree of water interaction (Cappa et al., 2018; Cappa et al., 2020). This also needs to be considered if other food applications are intended for bran powder (e.g., thickening agent in creamy products).

3.2. Physicochemical and nutritional characterization of raw rice

Table 4 shows significant ($p \leq 0.05$) differences in moisture among the samples. However, all values were lower than 14 g/100 g, thus according to Champagne (2004) and considering that they were packaged under vacuum, they could be stored at room temperature (20–25 °C) without microbial damage. The significant ($p \leq 0.05$) increase in moisture between brown and milled samples is ascribed to the processing conditions used and to the removal of the external rice layer which can expose the inner layers of the rice to moisture more readily, impacting the overall moisture content of the milled rice. The milling process impacts the physical and nutritional properties of rice grains. As expected, milling led to a significant ($p \leq 0.05$) reduction in kernel dimension (7–17%) and hardness (3–12%) due to the removal of 7–10% of the external layers (e.g., bran), which consists of insoluble fibers (e.g., cellulose and lignin) and proteins (Liu et al., 2021). The protein content in rice is directly correlated with its hardness; higher protein levels generally lead to greater hardness and reduced cohesiveness and stickiness (Aznan, Viejo, Pang, & Fuentes, 2023; Cameron & Wang, 2005). Therefore, the milling process that reduces protein content presumably reduces rice hardness. This assertion is supported by the data from our study (Table 4). Furthermore, Kalpanadevi, Singh, and Subramanian (2019) observed texture differences among the different rice varieties. In addition to protein content, these differences may also be due to variations in amylose content. In particular, rice with a lower amylose content is generally less hard (Aznan et al., 2023). Rocchetti et al. (2022) reported amylose content of 10.8 ± 1.2 g/100 g d.m. for Orange and 17.8 ± 1.1 g/100 g d.m. for Violet samples. For Carnaroli rice, amylose content varies from 15.5 to 24.41 g/100 g of d.m., and the protein content is 7.2 g/100 g of d.m. (Vici et al., 2021), followed by Orange and Violet rice (9.1 ± 0.03 and 10.0 ± 0.06 g/100 g of d.m., respectively; Rocchetti et al., 2022). On the contrary, the textural results of our samples (Table 4) show significantly ($p \leq 0.05$) higher hardness for BC, while BV and BO have lower hardness values. These results are probably due to the different amylose and protein contents compared to those reported in the literature.

Rice kernels before and after cooking are shown in Fig. 1. As expected, and in accordance with our previous study (Colombo et al., 2023), the colorimetric indices of raw samples were significantly ($p \leq 0.05$) affected by milling (Fig. 2) which caused an increase in lightness and a decrease in the other color coordinates due to the outer layer removal. The differences among samples could be detected by the naked eye (De Souza & Fernández, 2011), as the ΔE values, calculated between the raw brown and milled samples, ranged between 18.7 and 20.7 for the pigmented rice varieties and 5.7 for the Carnaroli sample (data not shown).

Both rice appearance (e.g., dimensions and color) and nutritional quality were affected by the rice variety and milling process. Pigmented varieties contain molecules responsible for the rice color (Bordiga et al., 2014). The nature of the red color is still unclear, but these varieties are rich in proanthocyanidins and phlobaphenes (Finocchiaro et al., 2007). Purple and black colors of the grains are associated with the presence of anthocyanins which are correlated with antioxidant capacity in black rice (Rowicka et al., 2018).

The total anthocyanin content (TA) was measured in raw and cooked Violet samples (Fig. 3), as some pigmented varieties do not contain anthocyanins, and the color could be due to the presence of proanthocyanidin and phlobaphens (Bani, Di Lorenzo, Restani, Mercogliano, & Colombo, 2023; Ciulu, de la Luz Cádiaz-Guerrea & Segura-Carretero, 2018). The raw BV sample showed a TA of 2.84 ± 0.25 mg CY/g d.m. (Fig. 3), which aligns with Fracassetti et al. (2020), where values of 1.83 and 3.41 mg CY/g d.m. in two different black rice varieties were reported. Catena et al. (2019) reported a greater TA concentration in a Violet rice sample than in our study (4.66 ± 0.03 mg/g d.m. *vs.* 2.84 mg/g d.m.). These differences could be attributed to the agronomic

Table 3
Fractioned rice bran physicochemical properties.

Code	L*	a*	b*	Moisture (g/100g)	WBC (g/g, wet basis)
BrV	42.21 ± 0.92^{a}	2.74 ± 0.18^{b}	1.76 ± 0.21^{a}	9.49 ± 0.07^{a}	2.95 ± 0.13^{b}
BrO	59.47 ± 0.39^{b}	4.07 ± 0.15^{c}	12.01 ± 0.26^{b}	9.74 ± 0.29^{a}	2.37 ± 0.25^{a}
BrC	76.84 ± 0.23^{c}	0.29 ± 0.15^{a}	12.44 ± 0.19^{c}	9.52 ± 0.05^{a}	2.17 ± 0.01^{a}

Note: Note: L*, lightness; a*, green–red index; b*, blue–yellow index; WBC, water binding capacity; BrV, bran from Violet rice; BrO, bran from Orange rice; BrC, bran from Carnaroli rice; in the same column, values followed by different letters are significantly different ($p \leq 0.05$).

Table 4
Physicochemical and nutritional properties of the raw rice kernels.

Code	Moisture (g/100g)	Length (mm)	Width (mm)	Length/Width	Area (mm^2)	Hardness max (N)	Hardness (N/mm^2)	TPC (mg GAE/g d.m.)	AOA (mg GAE/g d.m.)
BV	$13.39 \pm 0.15^{a,A}$	$6.17 \pm 0.27^{b,B}$	$2.68 \pm 0.18^{b,B}$	$2.31 \pm 0.18^{c,B}$	$13.26 \pm 1.02^{b,B}$	$782.21 \pm 69.51^{b,B}$	$11.80 \pm 1.05^{d,A}$	$6.912 \pm 0.443^{d,B}$	$2.211 \pm 0.287^{d,B}$
MV	$14.02 \pm 0.02^{c,B}$	$5.59 \pm 0.32^{a,A}$	$2.52 \pm 0.17^{a,A}$	$2.23 \pm 0.18^{b,A}$	$11.03 \pm 0.95^{a,A}$	$633.16 \pm 57.93^{a,A}$	$11.48 \pm 1.05^{cd,A}$	$2.753 \pm 0.156^{c,A}$	$0.897 \pm 0.063^{c,A}$
BO	$13.99 \pm 0.09^{c,A}$	$6.83 \pm 0.29^{c,B}$	$2.85 \pm 0.17^{c,B}$	$2.40 \pm 0.16^{d,B}$	$15.58 \pm 1.37^{c,B}$	$840.73 \pm 99.07^{bc,B}$	$10.80 \pm 1.27^{bc,B}$	$1.610 \pm 0.019^{b,B}$	$0.316 \pm 0.004^{b,B}$
MO	$14.42 \pm 0.08^{d,B}$	$6.21 \pm 0.33^{b,A}$	$2.74 \pm 0.18^{b,A}$	$2.28 \pm 0.19^{bc,A}$	$13.40 \pm 1.17^{b,A}$	$638.69 \pm 82.47^{a,A}$	$9.53 \pm 1.23^{a,A}$	$0.423 \pm 0.015^{a,A}$	$0.088 \pm 0.006^{a,A}$
BC	$13.70 \pm 0.01^{b,A}$	$7.41 \pm 0.27^{e,B}$	$3.34 \pm 0.10^{d,A}$	$2.22 \pm 0.09^{b,B}$	$20.12 \pm 1.15^{e,B}$	$1032.64 \pm 80.13^{d,B}$	$10.27 \pm 0.80^{ab,B}$	$0.596 \pm 0.005^{a,B}$	$0.151 \pm 0.003^{ab,B}$
MC	$13.82 \pm 0.16^{bc,A}$	$7.11 \pm 0.24^{d,A}$	$3.36 \pm 0.10^{d,A}$	$2.12 \pm 0.08^{a,A}$	$18.74 \pm 1.01^{d,A}$	$877.28 \pm 41.11^{c,A}$	$9.36 \pm 0.44^{a,A}$	$0.301 \pm 0.007^{a,A}$	$0.071 \pm 0.004^{a,A}$

Note: TPC, total phenolic content; AOA, antioxidant activity; GAE, gallic acid equivalents; BV, brown Violet; MV, milled Violet; BO, brown Orange; MO, milled Orange; BC, brown Carnaroli; MC, milled Carnaroli. In the same column, values followed by different lower letters are significantly different ($p \leq 0.05$). Among samples belonging to the same rice variety but treated differently (e.g., brown or milled), values followed by different uppercase letters are significantly different ($p \leq 0.05$).

variability of the rice collected in different years and the different techniques used to quantify the anthocyanins. Additionally, it is well known that environmental conditions play a crucial role in anthocyanin synthesis. Factors such as light exposure, soil pH, and temperature impact the biochemical pathways involved in anthocyanin production (Hayashi, Ohara, & Tsukoi, 1996; Yang et al., 2018). Furthermore, the quality and quantity of phytocompounds are greatly influenced by processing factors such as drying, extraction, isolation, and purification (Da Porto & Natolino, 2018; Sharma & Dash, 2022b). Analytical techniques used for the extraction and quantification of anthocyanins can lead to variations in measured levels. Different methods may vary in their efficiency and sensitivity, leading to discrepancies in the reported anthocyanin content (Alappat & Alappat, 2020). Raw MV had lower TA content (1.17 ± 0.06 mg CY/g d.m.) compared to raw BV (58.9%), probably because the milling process removes outer layers rich in these compounds (Mbanjo et al., 2020).

The total phenolic content (TPC) and antioxidant activity (AOA) were determined for all the samples (Table 4). As expected, the TPC of non-pigmented rice was lower than that of pigmented varieties (Orange and Violet). TPC values for brown samples from Carnaroli, Orange and Violet were 0.596 ± 0.005, 1.610 ± 0.019 and 6.912 ± 0.443 mg GAE/g d.m., respectively. These data align with finding from Min, McClung, and Chen (2014) who reported TPC values ranging from 0.30 to 7.03 mg GAE/g flour (d.m.) for six rice varieties with different pigmentation (from white to purple) and findings from Bordiga et al. (2014) who reported TPCs ranging from 1.4 ± 0.3 mg GAE/g d.m. (white cultivar) to 11.9 ± 1.2 mg GAE/g (d.m.) (black cultivar). The milling procedure significantly ($p \leq 0.05$) reduced the TPC by 60.2%, 73.7% and 49.5% in Violet, Orange and Carnaroli samples respectively. Phytochemicals, including the molecules responsible for the color of grains, generally accumulate in the pericarp or in the bran of rice kernels, and are removed by the milling process (Bordiga et al., 2014; Mbanjo et al., 2020). In agreement, a negative linear correlation ($r = -0.863$, $p < 0.05$) was found between rice lightness and TPC values confirming that the abrasive treatment (i.e., milling) that increased lightness values, reduced TPC.

The AOA measured using the DPPH assay, was highest in BV (2.211 ± 0.287 mg GAE/g d.m.), followed by BO (0.316 ± 0.004 mg GAE/g d.m.) and BC (0.151 ± 0.003 mg GAE/g d.m.). The milling process significantly ($p \leq 0.05$) reduced AOA by 59.4% in Violet, 72.3% in Orange and 53.4% in Carnaroli samples; in fact, a negative linear correlation ($r = -0.823$, $p < 0.05$) was found between rice lightness and AOA values, while a positive correlation ($r = 0.996$, $p < 0.001$*)* between the TPC and AOA was observed. These results agree with previous studies. Colombo et al. (2023) found that technological treatments such as milling and parboiling significantly ($p \leq 0.05$) influenced the TPC and AOA of Italian pigmented rice varieties. Particularly, milling led to reductions in soluble TPC of 46%, 70% and 77% respectively for the Carnaroli, Violet and Orange varieties, also causing decreases in AOA values of between 32% and 76%. In addition, lightness values, increased after the milling process. Similarly, Petroni et al. (2017) focused on a non-pigmented variety, revealing a decline in total soluble polyphenol content after processing. Furthermore, Finocchiaro et al. (2007) observed a decrease in total antioxidant activity in both white and red Italian rice varieties after different degrees of milling between 3% and 6%. Particularly, the AOA in red rice showed substantial reductions of 70% and 80% related to the degree of milling. In summary, rice processing significantly alters both the nutritional composition and antioxidant characteristics, particularly affecting pigmented rice varieties (Colombo et al., 2023).

3.3. *Physicochemical and nutritional characterization of cooked rice*

Rice cooking behavior and nutritional quality were analyzed based on the different processes to which they were subjected (Table 5). Cooked rice appearance (e.g., color, geometrical aspects) was assessed

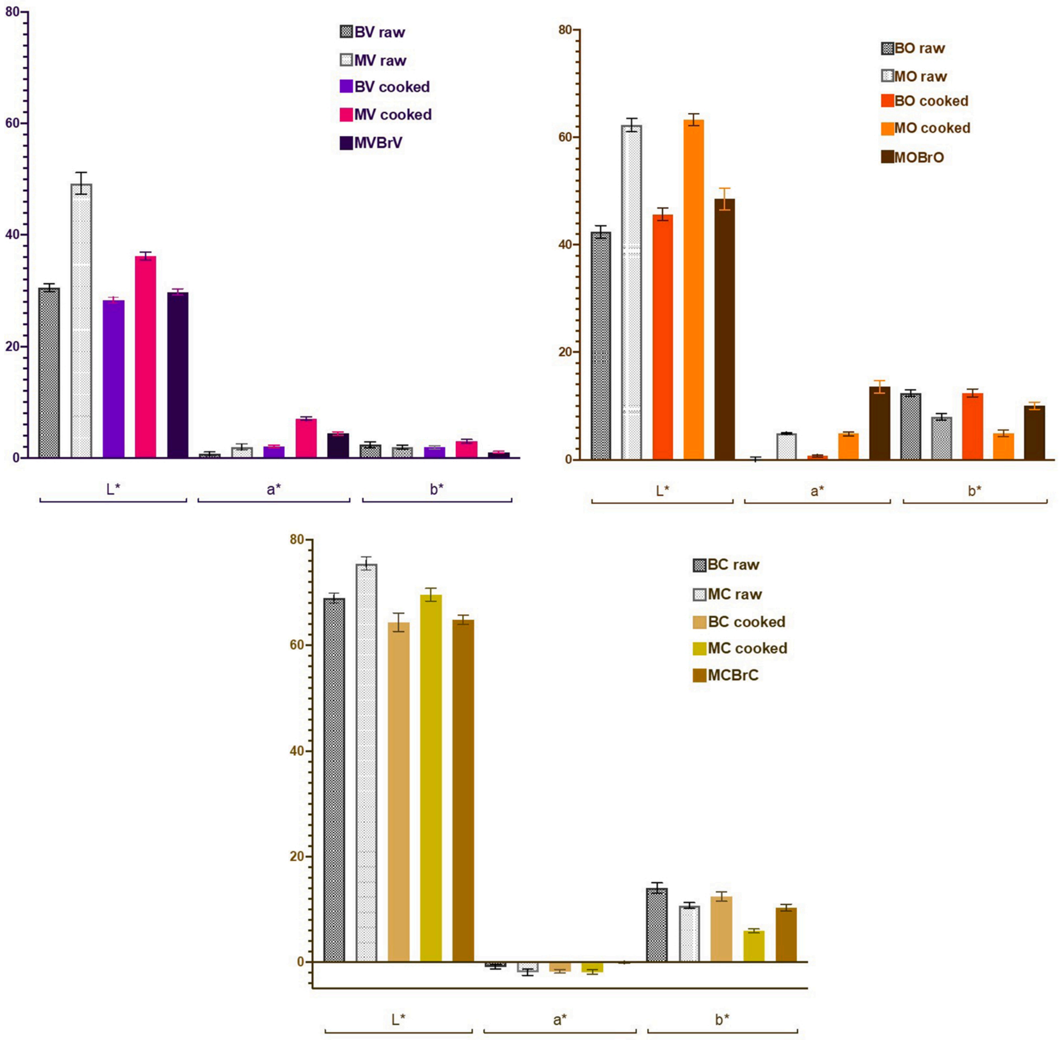

Fig. 2. Color indices of raw and cooked rice varieties (V, Violet; O, Orange and C, Carnaroli) subjected to different treatments (B, brown; M, milled; Br, with bran addition).

as its crucial for consumers perceptions. Milled samples presented significantly ($p \leq 0.05$) higher L* values compared to corresponding brown samples, regardless of the rice variety considered. However, the a* and b* values generally decreased, except for the Violet sample, indicating migration of pigmented compounds to the kernel surface during cooking. In fact, cooking led to a tiny reduction in pigmented compounds due to the high sample-to-water ratio used during the “risotto” cooking procedure (Table 1) compared to the traditional boiling method which leads to a high leakage of pigmented compounds in cooking water (Buratti, Cappa, Benedetti, & Giovanelli, 2020; Fracassetti et al., 2020). Color changes were visible to the human eye as ΔE values, calculated for cooked brown and milled samples compared to raw samples, ranged between 2.38 and 14.03 (MO and BV, respectively). Incorporating bran during cooking limited color loss. In fact, when comparing milled samples mixed with bran during cooking to cooked milled samples, significant ($p \leq 0.05$) increases in a* and b* were detected for the Orange and Carnaroli samples, while the MVBrV sample exhibited a lower redness value compared to cooked MV, but a higher value than raw MV; this can be partially attributed to the high increase of redness that already occurred during MV cooking due to the migration of pigmented compounds to the kernel surface, as can be seen in Fig. 1. The length, width, area, and their increments after cooking (Tables 5 and 7_S1) were determined through image analysis. As expected, all the samples absorbed water during cooking, reaching 77% higher moisture content and 56% greater kernel area. This trend was consistent across raw samples: Carnaroli showed the highest absorption, followed by Orange and Violet. Compared with brown samples, milled samples also exhibited greater geometrical increases (length >26.41%, width >28.83%, area >59.55%; data not shown). This finding suggested that the removal of the external layer enabled more water to enter the kernel resulting in a less rigid kernel structure that easily expanded during cooking. Additionally, water penetrated the kernel faster, as indicated by the shorter (47–59%) cooking time of the milled sample compared to that of brown rice (Table 1).

The weight increase (WI; data not shown), which indicates the amount of water absorbed by the sample during cooking, was 24% higher in the milled sample; thus, partial milling greatly affected rice cooking behavior. Additionally, the milled samples mixed with bran showed the most significant increase in dimension ($p \leq 0.05$). This may be due both to the milled rice’s capacity to expand more in width and length as well as to the added bran. Indeed, bran is rich in fiber and has a high WBC. Regarding the WI in samples with added bran, MVBrV showed the greatest increase (220% *vs.* 202% for MCBrC and 201% for MOBrO), which was consistent with the bran WBC data (Table 3).

Kernel water absorption during cooking also affects the texture of cooked rice, which is one of its most important attributes for consumers. In general, the cooking process led to a significant ($p \leq 0.05$; Table 7_S1) reduction in rice kernel hardness; this is partially due to the water

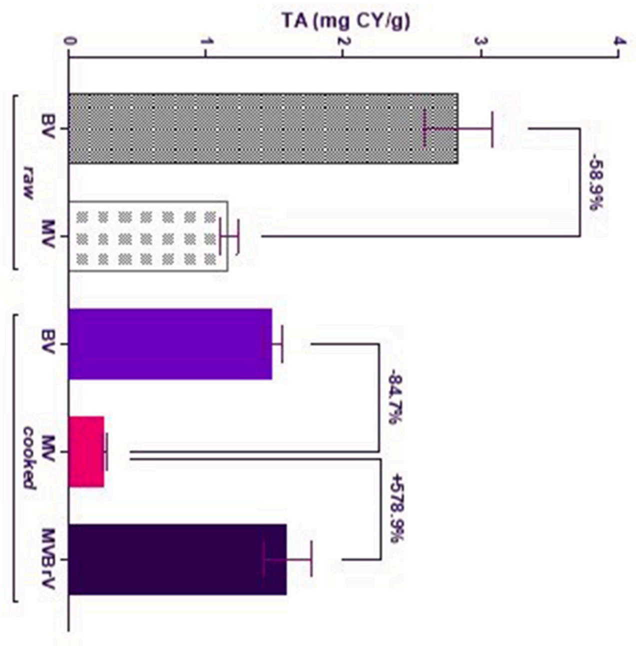

Fig. 3. Total anthocyanin (TA) content of the Violet rice samples. The results are expressed as equivalents of cyanidin-3-*O*-glucoside (mg CY/g d.m.) MV: milled Violet rice; BV: brown Violet rice; MVBrV: milled Violet rice with Violet bran.

absorption in fact an inverse correlation ($r = -0.905$, $p < 0.01$) was found between rice moisture and hardness values. Moreover, rice hardness was affected by rice variety and proximate composition. For instance, a positive relationship between amylose and protein content has been reported in the literature (Li & Gilbert, 2018; Vici et al., 2021). However, these are not the only factors affecting rice texture. For instance, cooking time, temperature and method can affect textural properties as stated by Tien, Phi, Thu, Oanh, and Van Hung (2024), as well as the rice process applied. In fact, for our samples significant ($p \leq 0.05$) differences were noted among samples treated differently (e.g., milled *vs*. brown; Table 5).

Among the various groups, the brown samples had the highest hardness, despite longer cooking times (Table 5). This finding suggested that the untreated samples (i.e., brown) had a more compact and organized structure, while milling weakens rice kernel structure. Among varieties, Carnaroli brown rice had the highest harness values, even if the value is normalized by kernel dimension (1.00 N/mm^2), while the MCBrC the lowest (0.31 N/mm^2).

To explore the effect of cooking on the loss of bioactive compounds, rice samples were prepared as “risotto”, as this preparation method better preserves anthocyanins (Bordiga et al., 2011; Finocchiaro et al., 2010; Zaupa et al., 2015). In general, cooked rice samples showed a significant ($p \leq 0.05$) reduction in TA content compared to raw samples (Table 7_S1), with a greater reduction observed in milled samples (79.0%) than in brown samples (43.7%). These results align with studies of Colasanto et al. (2021) who observed a TA reduction of 71% after “risotto” cooking, and of Fracassetti et al. (2020) who reported that TA decreased by 59.1% and 48.2% in Venere and Artemide cultivars, respectively. Furthermore, Zaupa et al. (2015) reported a reduction in TA of 30% and 64% in "risotto" and boiled rice, respectively.

After cooking the brown samples, the TPC significantly ($p \leq 0.05$; Table 7_S1) decreased by 15.5% in the Violet variety while it increased by 7.8% in the Orange variety compared to raw samples (Table 4). However, there was no significant difference in the TPC ($p > 0.05$; Table 7_S1). As expected, TPC of Carnaroli was lower than that of the pigmented varieties. The milling significantly ($p \leq 0.05$; Table 7_S1)

Table 5
Physicochemical and nutritional properties of cooked rice kernels.

Code	Moisture (g/100 g)	Length (mm)	Width (mm)	Length/Width	Area (mm^2)	Hardness max (N)	Hardness (N/mm^2)	TPC (mg GAE/g d.m.)	AOA (mg GAE/g d.m.)
BV	59.52 ± 0.56^{b,A}	7.19 ± 0.49^{a,A}	3.28 ± 0.36^{a,A}	2.21 ± 0.25^{c,B}	17.30 ± 2.20^{a,A}	77.10 ± 11.97^{d,C}	0.86 ± 0.15^{f,B}	5.839 ± 0.528^{f,C}	1.902 ± 0.099^{e,C}
MV	65.56 ± 0.39^{d,B}	7.43 ± 0.50^{b,B}	3.44 ± 0.36^{b,B}	2.18 ± 0.23^{c,B}	19.25 ± 1.99^{b,B}	45.57 ± 7.21^{a,A}	0.47 ± 0.08^{bc,A}	0.820 ± 0.076^{b,A}	0.298 ± 0.033^{c,A}
MVBrV	69.74 ± 1.07^{f,C}	7.81 ± 0.53^{c,C}	3.81 ± 0.33^{d,C}	2.06 ± 0.19^{ab,A}	21.15 ± 2.10^{c,C}	53.59 ± 8.17^{b,B}	0.51 ± 0.08^{c,A}	4.838 ± 0.633^{e,B}	1.648 ± 0.163^{d,B}
BO	59.43 ± 1.44^{b,A}	7.95 ± 0.46^{c,A}	3.68 ± 0.32^{c,B}	2.18 ± 0.21^{c,B}	22.20 ± 2.24^{d,B}	89.33 ± 13.25^{e,B}	0.81 ± 0.12^{e,C}	1.736 ± 0.069^{d,C}	0.286 ± 0.026^{c,B}
MO	63.55 ± 0.76^{c,B}	7.85 ± 0.49^{c,A}	3.53 ± 0.29^{b,A}	2.23 ± 0.22^{c,B}	21.38 ± 2.25^{c,A}	65.57 ± 12.87^{c,A}	0.61 ± 0.13^{d,B}	0.301 ± 0.021^{a,A}	0.066 ± 0.003^{a,A}
MOBrO	67.83 ± 0.74^{e,C}	8.37 ± 0.53^{d,B}	4.21 ± 0.40^{e,C}	2.00 ± 0.21^{a,A}	25.82 ± 2.37^{e,C}	69.38 ± 7.64^{c,A}	0.54 ± 0.06^{c,A}	1.353 ± 0.126^{c,B}	0.336 ± 0.016^{c,C}
BC	55.37 ± 0.66^{a,A}	8.89 ± 0.38^{e,A}	4.27 ± 0.29^{e,A}	2.09 ± 0.14^{b,B}	30.14 ± 2.47^{f,A}	150.10 ± 24.52^{f,B}	1.00 ± 0.15^{g,C}	0.608 ± 0.035^{ab,B}	0.136 ± 0.022^{ab,B}
MC	62.75 ± 0.68^{c,B}	9.98 ± 0.49^{f,B}	4.54 ± 0.29^{f,B}	2.18 ± 0.16^{c,C}	33.87 ± 2.47^{g,B}	70.49 ± 15.78^{cd,A}	0.41 ± 0.10^{b,B}	0.321 ± 0.024^{a,A}	0.078 ± 0.008^{a,A}
MCBrC	67.17 ± 0.31^{e,C}	10.60 ± 0.75^{g,C}	5.41 ± 0.48^{g,C}	1.97 ± 0.18^{a,A}	41.22 ± 4.53^{h,C}	63.57 ± 10.71^{c,A}	0.31 ± 0.05^{a,A}	0.680 ± 0.019^{b,C}	0.194 ± 0.009^{b,C}

Note: n.d., not determined; TCP, total phenolic content; AOA, antioxidant activity; GAE, gallic acid equivalents; BV, brown Violet; MV, milled Violet, MVBrV, milled Violet with Violet bran addition; BO, brown Orange; MO, milled Orange; MOBrO, milled Orange with Orange bran addition; BC, brown Carnaroli; MC, milled Carnaroli; MCBrC, milled Carnaroli with Carnaroli bran addition. In the same column, values followed by different lower letters are significantly different ($p \leq 0.05$). Among samples belonging to the same rice variety but treated differently (e.g., brown, milled or milled but added with bran), values followed by different uppercase letters are significantly different ($p \leq 0.05$).

reduced the TPC by 86%, 83%, and 47% in the Violet, Orange and Carnaroli samples, respectively. Different studies show contrasting effects of thermal processes on TPC, reporting both a decrease (Fracassetti et al., 2020; Mbanjo et al., 2020; Melini et al., 2019) and an increase (Dewanto, Wu, & Liu, 2002; Zielinski, Kozlowska, & Lewczuk, 2001). This discrepancy could be related to various influencing factors, such as the plant species or the cooking procedures applied. The increase in free phenolic stability could be explained by the release of insoluble, cell wall-bound phenolics during thermal treatment (Mbanjo et al., 2020).

After cooking, Fracassetti et al. (2020) observed a decrease in phenolic compound content of 31.7% in Carnaroli and 58.3% and 71.7% in the two black rice varieties. Melini et al. (2019) noted reductions ranging from 5% to 40% in free phenolic molecules after preparing six pigmented rice varieties as "risotto". Interestingly, Melini et al. (2019) reported that black rice varieties were more resistant to thermal treatments than red rice varieties. The loss of TPC could be due to factors such as migration of biocompounds into cooking water, chemical degradation or conversion into other compounds, and interactions with other food components, thus reducing their extractability (Zielinski et al., 2001). Compared to other cooking methods, the "risotto" preparation may thus reduce the loss of phenolics by completely absorbing the added water.

Compared to raw samples, the AOA in the cooked brown samples (Table 4) decreased by 14%, 9.3%, and 9.8% in the Violet, Orange and Carnaroli varieties, respectively. Moreover, milled pigmented samples showed a significant ($p \leq 0.05$; Table 7_S1) reduction in AOA after cooking for MV and MO (67% and 25% respectively) samples, while MC was slightly affected.

The milled Violet sample mixed with bran from Violet (MVBrV) during cooking had a very similar TA (1.67 ± 0.14 mg CY/g d.m.) to that of cooked BV (1.60 ± 0.16 mg CY/g d.m.). Moreover, an increase of 579% in terms of TA was observed when comparing MVBrV to cooked MV. All the samples cooked with added bran (MVBrV, MOBrO, and MCBrC) exhibited significantly ($p \leq 0.05$) higher TPC (112-490%) and AOA (150-453%) values compared to the corresponding cooked milled samples (MV, MO, and MC). These results are supported by findings from our previous study (Colombo et al., 2023), which indicated that bran obtained from the milling process contain a considerable quantity of anthocyanins, as measured by both spectrophotometric and chromatographic methods. Specifically, the anthocyanin content was recorded at 25.62 ± 3.45 mg CY/g and 18.09 ± 0.26 mg/g, respectively. Furthermore, the study found that bran contains a substantial quantity of soluble phenolic compounds. The measured values were 40.17 ± 0.65 mg GAE/g in Violet bran, 9.65 ± 0.10 mg GAE/g in Orange bran, and 5.15 ± 0.68 mg GAE/g in Carnaroli bran. According to the soluble phenolic content, the antioxidant activity measured in bran co-products was 16.14 ± 0.12 mg GAE/g in Violet bran, 2.26 ± 0.14 mg GAE/g in Orange bran, and 1.21 ± 0.11 mg GAE/g in Carnaroli bran. Although not reaching the level of brown samples, this approach might enhance the nutritional and beneficial properties of milled rice; thus, consumers could consume rice with improved nutritional properties, in a relatively short cooking time.

3.4. *Impact of the addition of pigmented bran to non-pigmented rice*

As one of the aims of the study was to recover a co-product of rice milling and enhance pigmented rice, Violet or Orange bran powder (10% weight relative to the amount of rice) was added to the milled Carnaroli rice 5 min before the end of cooking to assess physicochemical and/or nutritional improvements. The rice-to-water ratio was kept equal to 50 g to 210 mL, and the cooking time was 18 min, as these conditions were already found to be the best for Carnaroli rice (MCBrC). The addition of Violet or Orange bran powders significantly ($p \leq 0.05$) affected rice color (Fig. 4, Table 6). Moreover, the MCBrV and MCBrO samples appeared creamier than the MVBrV and MOBrO samples. This could be due to the high amylose content of Carnaroli rice, which is responsible for its typical "starchy cream" formation. No significant ($p > 0.05$) differences in texture parameters were found among MCBrC, MCBrO and MCBrV, suggesting that texture was mainly affected by rice variety and that a "creamy soft risotto" can be prepared regardless of the type of bran added.

The milled Carnaroli sample with added Violet bran (MCBrV) had a very similar TA (1.25 ± 0.10 mg CY/g d.m.) to the TA of the cooked BV sample (1.60 ± 0.16 mg CY/g d.m., Fig. 3). Additionally, when Violet or Orange bran was added to Carnaroli rice (MCBrV and MCBrO, respectively), the final TPC was similar to that of MV and MO rice with the corresponding added brans (MVBrV, MOBrO; Table 5; $p > 0.05$). These findings suggest that adding Violet or Orange bran to MC rice increased the TPC by approximately 131% and 625%, respectively, compared to the BC sample, thus enhancing the functional quality of common rice. The AOA showed a similar trend, confirming that adding pigmented brans to non-pigmented milled sample can improve the nutraceutical properties of "risotto" by reducing cooking time in respect to brown rice. Therefore, while halving the cooking time, consumers could consume common rice varieties with nutritional properties to those of pigmented brown rice.

Rice bran is a notable source of phenolic compounds like anthocyanins and proanthocyanidins (Colombo et al., 2023), offering several advantages but also presenting some challenges. Rich in these beneficial compounds, rice bran can contribute to potential health benefits, including antioxidant, anti-inflammatory, and cardiovascular protective effects (Shuai et al., 2024). Moreover, the re-use of rice bran supports sustainable practices by reducing waste. However, the extraction of phenolic compounds like anthocyanins from rice bran can be technically challenging. Polyphenols present low bioavailability due to several factors: interaction with the food matrix, metabolic processes mediated by the liver (phase I and II metabolism), intestine and microbiota (Di Lorenzo, Colombo, Biella, Stockley, & Restani, 2021). Despite these drawbacks, the advantages of rice bran make it an attractive option for enhancing both human health and sustainability in the food industry.

Fig. 4. Milled Carnaroli rice were cooked with the addition of 10% Carnaroli, Orange or Violet bran powders (MCBrC, MCBrO, and MCBrV, respectively) from left to right.

Table 6
Physicochemical and nutritional properties of milled Carnaroli rice cooked after the addition of pigmented bran powders.

Code	L*	a*	b*	Fmax (N)	Hardness (N/mm^2)	TA (mg CY/g d.m.)	TPC (mg GAE/g d.m.)	AOA (mg GAE/g d.m.)
MCBrC	64.85 ± 0.90^{c}	-0.01 ± 0.18^{a}	10.36 ± 0.65^{b}	63.57 ± 10.71^{a}	0.31 ± 0.05^{a}	n.d.	0.680 ± 0.019^{a}	0.194 ± 0.009^{a}
MCBrO	29.5 ± 0.25^{b}	4.67 ± 0.34^{b}	1.08 ± 0.23^{c}	59.14 ± 6.26^{a}	0.32 ± 0.03^{a}	n.d.	1.407 ± 0.075^{b}	0.388 ± 0.008^{b}
MCBrV	49.36 ± 1.63^{a}	4.65 ± 0.50^{b}	13.31 ± 0.66^{a}	61.56 ± 8.95^{a}	0.33 ± 0.05^{a}	1.250 ± 0.100	4.407 ± 0.235^{c}	1.835 ± 0.032^{c}

Note: The MCBrC sample data are already reported in Fig. 2 and Table 4; however, they are reported here for statistical comparison. n.d., not determined; TA, total anthocyanin content; TPC, total phenolic content; AOA, antioxidant activity; CY, cyanidin-3-*O*-glucoside; GAE, gallic acid equivalents; MCBrC, milled Carnaroli with Carnaroli bran addition; MCBrO, milled Carnaroli with Orange bran addition; MCBrv, milled Carnaroli with the addition of Violet bran. In the same column, values followed by different letters are significantly different ($p \leq 0.05$).

The addition of pigmented rice bran to cooked non-pigmented rice affects various aspects, including color, moisture, texture, anthocyanin content, total phenolic content, and antioxidant activity. Cooked rice enriched with pigmented bran adopts a darker color, such as red, purple, or black, due to the natural pigments transferred by the bran. We hypothesize that the increase in anthocyanin and total phenolic content is due to the temperature and water used during rice cooking. The water enriched with phenolic compounds is then reabsorbed by rice during the "risotto" cooking method. This enrichment not only raises the concentration of anthocyanins and phenolics but also enhances the antioxidant activity of the cooked rice, making it more beneficial for health due to the ability of these compounds to neutralize free radicals and reduce oxidative stress (Tan & Norhaizan, 2017; Tan, Norhaizan, & Chan, 2023). To summarize, incorporating pigmented rice bran not only improves the phytochemical profile of non-pigmented rice but also promotes sustainable practices by reducing food waste.

4. Conclusion

This study examined the effects of milling on the raw rice quality of pigmented and non-pigmented varieties compared to brown samples, while also exploring how cooking can affect physicochemical characteristics, phenolic compounds and antioxidant activity of the different rice varieties. The “risotto” cooking method was employed to better preserve water-soluble compounds compared to traditional boiling methods involving large amounts of water that are discharged. The findings of our study revealed a notable reduction in cooking time by 47–59% due to milling, although accompanied by a substantial (50-74%) loss of phenolic compounds *vs.* raw brown sample of the same variety. Reintroducing bran, typically removed during milling, in the cooking process proved effective as a means of enhancing rice, paving the way for innovative applications of this ingredient after powdering and sieving. Today, consumers prefer rice varieties with shorter cooking times (e.g., non-pigmented *vs.* pigmented rice, or milled instead of brown rice). However, the study demonstrates that it’s possible to maintain essential nutritional properties, such as quantity and bioactivity of antioxidant compounds, without compromising consumer convenience (i.e., cooking time). Moreover, the incorporation of bran powders derived from pigmented rice into Carnaroli rice yielded distinctive products characterized by interesting color profiles and increased polyphenol content. These findings have implication for both consumers and the industry, presenting a way to nutritionally enhanced rice. Further studies will be necessary to assess consumer reaction to the innovations presented here as well as the stability of bran during storage before it can be commercialized.

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CRediT authorship contribution statement

Corinne Bani: Writing – review & editing, Writing – original draft, Formal analysis. **Carola Cappa:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Patrizia Restani:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Data curation, Conceptualization. **Marianna Sala:** Writing – review & editing, Writing – original draft, Formal analysis. **Francesca Colombo:** Investigation, Data curation. **Francesca Mercogliano:** Formal analysis. **Chiara Di Lorenzo:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.lwt.2024.116653.

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