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Extruded snacks from pigmented rice: nutritional and physical properties

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Abstract

This study arose from the need to meet the request of consumers for healthy, ready-to-eat foods. The behavior of pigmented rice was investigated during extrusion in terms of nutritional (i.e., phenolic acids, anthocyanins and antioxidant capacity (AC)) and physical (i.e., starch pasting properties, texture, porosity and biometric indices) properties. Snacks were produced from brown, red, and black rice, by means of a co-rotating twin-screw extruder, and their features were compared with those of snacks from white rice.

Although the soluble and cell-wall bound phenolic acid contents of pigmented and brown rice did not differ, the red and black rice both resulted in a higher AC after extrusion. Black rice showed the highest anthocyanin and AC contents, even after extrusion. Furthermore, the high phenolic compound content of black rice affected the starch pasting properties, and led to a lower viscosity and higher snack porosity than those of brown rice. Nevertheless, considering both the biometric and textural properties, the best results were obtained from red rice. Optimizing the extrusion conditions will help reduce the loss of anthocyanins in snacks made of pigmented rice, increase the nutritional value and improve the physical properties of the product.

Keywords

phenolic acids; anthocyanins; antioxidant activity; extrusion

Abbreviations

ABTS, 2,2’-Azino-bis(3-ethylbenzthiazoline-6-sulfonic acid; AC, antioxidant capacity; AC-ABTS, antioxidant capacity obtained by means of an ABTS assay; AC-FRAP, antioxidant capacity obtained by means of a FRAP assay; ANOVA, analysis of variance; CY-3-GLC, cyanidin-3-*O*-glucoside; *cv*, cultivar; CWBPA, cell-wall bound phenolic acid; DW, dry weight; FRAP, Ferric Reducing Antioxidant Power; PE-3-GLC, peonidine-3-*O*-glucoside; REGWF, Ryan-Einot-Gabriel-Welsh F post-hoc test; RP-HPLC-DAD, reverse phase high-performance liquid chromatography-photodiode array detector; SPA, soluble phenolic acid; TAC, total anthocyanin content.

1 Introduction

Rice (*Oryza sativa* L.) is a staple food in many countries and is commonly consumed as white (polished or milled) rice, which is obtained by removing the bran and germ fractions from the kernels, to guarantee a longer storage and shelf-life and a better palatability after cooking. Nowadays, the awareness of consumers about the nutritional benefits of whole grains, which are characterized by a unique blend of bioactive compounds, with several phytochemicals exerting antioxidant capacity (AC), has led to a significant increase in their interest (Melini et al., 2019).

Rice bran contains large amounts of fiber and other bioactive compounds, including vitamin B complex, tocopherols, tocotrienols and oryzanols (Hu et al., 2018), whose consumption is related to several health benefits (e.g., enhancement of the immune system, and reduction in the risk of developing heart disease and cancer). Phenolic acids are the most common secondary metabolites in cereals. The large amount of phenolic acids in rice, as well as in other cereals, exists in an insoluble-bound form (Pang et al., 2018) and they directly influence their antioxidant capacity.

Moreover, some bioactive compounds are responsible for the color of the rice pericarp. For example, red rice is characterized by the presence of pro-anthocyanidins, which mainly consist of catechin and epicatechin block units (Gunaratne et al., 2013). Moreover, black rice contains anthocyanins, such as cyanidin-3-*O*-glucoside (Cy-3-glc) and peonidine-3-O-glucoside (Pe-3-glc) (Hiemori et al., 2009).

Rice is one of the most frequently used commodities in the gluten-free industry, as it is suitable for the production of ready-to-eat foods, such as snacks (Dalbhagat et al., 2019). Increased consumer attention to the nutritional aspects of food products has led to the demand for healthier and more nutritious snacks than those currently available on the market. However, healthier snacks that are rich in fiber may present some issues in physical features (i.e., structure and texture). Indeed, an increased hardness, due to a reduced expansion and density, is among the most critical effects of adding fiber to puffed snacks (Robin et al., 2012). On the other hand, there is still little information on the effect of fiber-enrichment on the physical features of co-extruded snacks. The latter are characterized by a compact structure, with an outer shell that is later filled with either a savory or sweet filling. Although the characterization of bioactive compounds in pigmented rice has been widely addressed (Bordiga et al., 2014; Melini et al., 2019; Pang et al., 2018; Shao et al., 2018), the effect of extrusion has only been investigated occasionally (Hu et al., 2018; Zhang et al., 2018).

Thus, the aim of this study has been to investigate the impact of extrusion on nutritional (i.e., the phenolic acid and anthocyanin contents and AC) and physical (including bulk density, porosity, and texture) features of snacks made of conventional and pigmented rice (i.e., red and black rice cultivars, *cvs*). The results of the present study could provide new insights into the raw materials that are more suitable for the production of healthy snacks.

2 Experimental

2.1 Rice flours

A conventional brown variety (*cv* Ellebi; Bertone Sementi, Terruggia, Italy; classified as long B), a pigmented red variety (*cv* Ermes; Sa.Pi.Se, Vercelli, Italy; classified as long B) and a pigmented black variety (*cv* Venere, Sa.Pi.Se, Vercelli, Italy; classified as medium) were kindly provided by Molino Peila S.p.A. (Valperga, Italy). The rice *cvs* were cultivated in the same growing area in North West Italy in the 2018 growing season.

De-husked kernels were ground into flour (70% of particle size < 220 µm) in a roller-miller (Bühler Group, Uzwil Switzerland). Bran was completely removed from the kernel of *cv* Ellebi to obtain a white rice that was then ground into flour.

Flours were stabilized by means of an infrared heat treatment (120°C for 10 min, RI/1550, Brovind, Cortemilia, Italy) in order to reduce humidity (<10%) and increase the shelf-life, but also to act on the bacterial load.

2.2 Snack production

Co-extruded snacks were produced at an industrial level by Fudex Group S.p.A. (Settimo Torinese, Italy). Extrusion was performed using a co-rotating twin-screw extruder (model 2FB90; screw speed: 100 rpm; temperature: 120 °C; pressure: 70 bar; feed moisture: 10%). The snacks were stored at room temperature and used without any pre-treatment for the analysis described in section 2.8. Prior to quantification of the antioxidant capacity and the antioxidant compound content, all the flour and snack samples were ground to a fine powder (particle size < 500 µm) in a Cyclotec 1093 sample mill (Foss, Padova, Italy), and stored at -25°C until the beginning of the analyses.

2.3 Proximate composition

The moisture content of both the flours and snacks was determined by oven-drying at 105 °C for 24 h. All the results were expressed on a dry weight (dw) basis.

The chemical composition was only determined for the rice flours. The total starch content was measured according to the standard AACC 76-13.01 method (AACC, 2001), the total protein content according to the AOAC 990.03 (Dumas method conversion factor: 5.7), the total dietary fiber according to the AOAC 985.29, enzymatic-gravimetric method, while the fat (AOAC 2003.05, Soxhlet method) and ash (AOAC 923.03, muffle furnace) contents were determined according to the AOAC (2005) procedures.

2.4 Soluble (SPA) and cell wall-bound (CWBPA) phenol acids

The extraction and quantification of the SPAs (free and conjugated) and CWBPAs were performed according to the procedure reported by Giordano et al. (2019).

The phenolic extracts were filtered through a 0.2 µm filter and then analyzed by means of an Agilent 1200 Series (Agilent Technologies, Santa Clara, CA, USA) high-performance liquid chromatograph coupled with an Agilent 1200 series diode array detector. Separations were carried out using a 150 x 4.6 mm, 5 µm particle size Gemini RP-18 column (Phenomenex, Torrance, CA, U.S.A), as reported by Giordano et al. (2019).

2.5 Total anthocyanin content (TAC)

The TAC was determined by means of the pH differential method. Each sample (1 g) was extracted in 8 mL of ethanol acidified with 1 N HCl (85:15, v/v) for 30 min. After centrifugation at 20,800 x g for 2 min, the absorbance was read at 540 nm, as reported by Siebenhandl et al. (2007). TAC was expressed as mg Cy-3-glc equivalents/kg of sample (dw).

2.6 Antioxidant capacity (AC)

The total AC was determined by means of FRAP (Ferric Reducing Antioxidant Power) and ABTS [2,2'-Azino-bis(3-ethylbenzthiazoline-6-sulfonic acid)] assays adapted from the QUENCHER method, as described by Giordano et al. (2019).

The results were expressed, through a calibration curve, as mmol Trolox equivalents kg^{-1} of sample (dw).

2.7 Pasting properties

The pasting properties of both the flours and grinded snacks were evaluated using a Micro Visco-Amylo-Graph (Brabender GmbH., Duisburg, Germany), according to Bresciani et al. (2021), using 12 g samples in 100 ml of distilled water and adopting the following temperature profile: heating from 30 up to 95°C, holding at 95°C for 20 minutes and cooling from 95 to 30°C with a heat/cooling rate of 3°C min^{-1}.

2.8 Physical properties of the snacks

The section area and inner area of the cross sections of the snacks were measured by means of image analyses, as reported by Bresciani et al. (2021). Cylindrical shaped snacks were cut using a cutter, and images of the cross sections were acquired, at 300 dots per inch, with a digital scanner (Epson Perfection 550 Photo, Seiko Epson Corp., Suwa, Japan). The images were processed at the gray level (8 bits). Image analyses were performed using Image ProPlus software (v6; Media Cybernetics, Inc., Rockville, US).

Porosity and bulk density were assessed with a Pascal Mercury Porosimeter (P240; Thermo Fisher Scientific, Waltham, US), as reported by Bresciani et al (2021). Samples were subjected to an increasing pressure of up to 200 MPa, and pores with a radius of 3.7 × 10 −3 to 50 µm were measured. The textural properties of the snacks were determined, as reported by Bresciani et al. (2021), by means of the three-point bend method, using a TA – XT plus texture analyzer (Stable Micro Systems Ltd., Godalming, UK) equipped with a 10 kg (100 N) load cell.

2.9 Statistical analysis

The SPA and CWBPA contents, TAC and AC were measured in triplicate, whereas the image and texture analysis were carried out on ten and thirty pieces, respectively. The pasting properties, bulk density and porosity were measured in duplicate.

Analysis of variance (ANOVA) was performed with SPSS for Windows statistical package, Version 24 (SPSS Inc., Chicago, Illinois, USA). Significant differences (p<0.05) between the samples were determined using the Ryan-Einot-Gabriel-Welsh F (REGWF) test.

3 Results and discussion

3.1 Proximate composition

The chemical composition of the raw materials is shown in Supplementary Table 1. The differences between white and brown rice (belonging to the same *cv*) were consistent with those reported in the literature. The removal of the bran and germ fractions from the brown rice in fact led to white rice with lower amounts of lipids, fiber, and ash. The red rice cv showed the lowest fiber content (3.8 g 100 g^{-1}). On the other hand, no differences were detected for the starch, lipid, or ash contents between the conventional and pigmented rice *cvs*. The chemical composition of the pigmented rice agreed with recent findings on the same *cvs* (Melini et al., 2019).

3.2 SPA and CWBPA contents

The effect of the extrusion process on the SPAs and CWBPAs is shown in Figure 1. The brown, red, and black rice contained more SPAs and CWBPAs than the white rice, since these compounds are mostly concentrated in the bran fraction (Zhang et al., 2018). Indeed, the removal of bran from the conventional *cv* reduced the SPAs and CWBPAs by 71% and 63%, respectively. Ferulic, sinapic and hydroxybenzoic acids are the most abundant SPAs in white rice, with concentrations of 37%, 28% and 23%, respectively (considering the total SPA content). Instead, the above-mentioned phenolic acids represent 36%, 39% and 13%, respectively, of the total SPAs in brown rice. Considering the CWBPAs, ferulic, p-cumaric and sinapic acids are the most abundant compounds in both white and brown rice, with a higher contribution of *p*-cumaric to brown rice (25%) than to the white one (6%). The insoluble-bound forms, whereby the acids are esterified to cell walls, are more abundant than the soluble ones, including soluble-free and soluble-conjugated acids (Shao et al., 2014b). Ferulic and *p*-cumaric acid are the main phenolic acids in rice, and most of them are bound to cell wall polysaccharides and lignin (Zaupa et al., 2015).

The total phenolic acid content in the brown, red, and black rice was similar, while differences were observed in their relative composition. The brown and red rice samples showed a similar profile: sinapic (42%), ferulic (32%) and hydroxybenzoic (13%) acids were the most abundant SPAs, while ferulic (67%), *p*-cumaric (25%) and sinapic (6%) acids were the most abundant CWBPAs. Conversely, black rice resulted in a different phenolic acid composition: sinapic (35%), ferulic (28%) and vanillic (15%) acids were the most abundant SPAs, while ferulic (68%), protocatechuic (14%) and *p*-cumaric (8%) acids were the most abundant CWBPAs. In agreement with Shao et al. (2018), larger amounts of protocatechuic and vanillic acids were detected in black rice rather than in brown rice. The insoluble protocatechuic acid content (71.5 mg kg^{-1}) found in black rice was similar to that reported in previous works (Zaupa et al., 2015).

This is the first study that has directly compared the impact of extrusion on the total phenolic acid content of conventional (brown and white) and pigmented (red and black) rice *cvs*. So far, only black rice has been used to investigate the effects of either different extrusion temperature (Hu et al., 2018) or milling fractions (Ti et al., 2015) on the phytochemical and antioxidant properties of rice products.

The extrusion process resulted in a significant decrease (-16%) in SPAs, albeit only for black rice. Furthermore, extrusion also reduced the soluble sinapic acid and ferulic acid in the conventional white and brown rice *cvs*. The greatest reduction was detected for sinapic acid, that is, of 84%, 65% and 43% in white, black and brown rice, respectively. The ferulic acid content was reduced by 77%, 44% and 30%, in the white, black, and brown rice, respectively. Hu et al. (2018), studying the role played by the extrusion temperature, showed a reduction in the soluble sinapic and ferulic acid contents in black rice as the extrusion temperature increased, although quite similar reduction percentages (-62% and -40% for soluble sinapic and ferulic acids, respectively) to those of the present study were reached when the extrusion temperature was set at 120 °C. Moreover, Zhang et al. (2018) reported a significant decrease in soluble ferulic acid of 39%, after extruding brown rice at 120 °C.

The CWBPA content of all the *cvs* increased following extrusion: +33% for brown rice; +8.5% for red rice and +20% for black rice, although the increase was only significant for brown rice. An increase in the insoluble phenolic compounds occurred for brown rice, due to the polymerization of free phenolic acids, which consequently decreased upon extrusion. This result could be accentuated by the effect of increased temperature, pressure and shear force (Zeng et al., 2017). The highest increases detected for the more abundant CWBPAs were for hydroxybenzoic acid (+153%) and sinapic acid (+141%). A significant increase in protocatechuic acid (+32%) was only observed for black rice after extrusion. This effect is supposed to be due to the degradation of Cy-3-Glc, which is converted into protocatechuic acid (Hiemori et al., 2009). The *p*-cumaric, vanillic and ferulic acid contents remained approximately stable in all the samples after extrusion, in agreement with Ti et al. (2015). Zhang et al. (2018) highlighted that, in comparison with other thermal processing methods, extrusion usually has less effect on the phenolic acid contents of raw materials due to the short heat exposure time.

3.3 Total anthocyanin content (TAC)

The black rice showed a significantly higher TAC than the red and brown rice, in agreement with Bordiga et al. (2014). Previous works regarding the qualitative profile of anthocyanins in black rice consistently reported the prevalence of Cy-3-glc, which represents more than 80% of the total anthocyanin content in some varieties, and the presence of Pe-3-glc as the second most relevant anthocyanin (Melini et al., 2019; Shao et al., 2014a).

The TAC in red rice did not differ significantly from the value found in both the brown and white rice. There are conflicting data in the literature on the presence of anthocyanins in red rice. The TAC of red rice (17.8 mg kg^{-1}) in this study was similar to the one registered by

Ziegler et al. (2018) (13.8 mg kg^{-1}). Melini et al. (2019) found traces of malvidin in one of the three varieties of red rice they tested, and Pereira-Caro et al. (2013) observed Cy-3-glc in a red rice cultivar from France. In contrast, no anthocyanins were found in red rice varieties from Korea (Kim et al., 2010) or Sri Lanka (Gunaratne et al., 2013).

The extrusion of black rice significantly reduced the TAC by 90%, in agreement with Ti et al. (2015), who reported a TAC reduction of 88%. Despite the overall loss in TAC, the snacks from black rice maintained the highest value (Figure 2). Hu et al. (2018) instead reported that increasing the extrusion temperature from 90 °C to 110 °C did not affect the TAC content. They also observed a significant decrease in Cy-3-glc and Pe-3-glc contents when black rice was extruded at 90 °C. It has been observed that the cooking temperature is the factor that influences the stability of anthocyanins the most (Hiemori et al., 2009). The high extrusion temperature (120°C), together with high shear forces applied in the present study, may have reduced the TAC more consistently than other cooking processes reported in the literature.

3.4 Antioxidant capacity (AC)

The AC of the brown rice was significantly higher (+273% and +169% for FRAP and ABTS) than that of the white rice. A further significant increase in AC was detected in the red and black rice (+169% and + 154% for FRAP and ABTS, respectively), in accordance with previous studies (Pang et al., 2018; Shao et al. 2018). However, no differences were found between the red and black rice *cvs* (Figure 3). Whereas, in other studies, black rice exhibited a higher AC than red or brown rice (Zaupa et al., 2015).

The extrusion of the white rice did not affect the AC to any great extent. On the other hand, the AC_{ABTS} of the brown rice increased (+16%) after extrusion, likely due to the production of dark color pigments (particularly melanoidins), which are known to have antioxidant activity (Patil and Kaur, 2018). Conversely, as assessed in both of the AC assays, the extrusion process caused a decrease in AC of the red rice of -20% (ABTS) and -33% (FRAP). The AC of the black rice instead showed no significant differences after extrusion, although Ti et al. (2015) showed a decrease (-15%).

Phenolic compounds are among the substances that are mainly responsible for the antioxidant activity of rice (Shao et al., 2014b). The significant reduction in TAC and SPAs in the black rice following extrusion was possibly compensated by the increase in CWBPAs and the formation of other antioxidant compounds as a result of the Maillard reaction. Moreover, other classes of non-phenolic compounds (such as carotenoids and γ-oryzanols) present in rice can contribute to its antioxidant capacity. According to Melini et al. (2019), black rice has a greater nutraceutical potential than red rice. Focusing on the phytochemicals found in extruded snacks, our study has clearly highlighted the higher AC exerted in the final products of pigmented rice *cvs* than in conventional ones. The black rice in particular, despite the reduction observed after production, maintained a good anthocyanin content in the snacks (Figure 2). Moreover, this raw material seemed to prevent a drop in AC after the extrusion process, as observed for other *cvs* (Figure 3).

3.5 Pasting properties

The pasting profiles of the raw materials are reported in Figure 4. The brown rice showed a higher peak viscosity (538.5±20.5 BU) than the related white rice (429.5±26.1 BU), although the removal of bran from kernels generally leads to an increase in peak viscosity (Mariotti et al., 2009). The observed differences in peak viscosity could be due to bran, which absorbs water during heating, thus increasing the paste viscosity. On the other hand, the viscosity after cooling (final viscosity) was higher in white rice (733 ±35.3 *vs* 668 ±14.1 BU). This could be due to the higher starch content in white rice than in brown rice (Supplementary Table 1). The brown and red rice showed a higher peak viscosity (538.5±20.5 BU and 416±2.8 BU, respectively) than the black rice (306 ±31.1 BU). During cooling, the lowest final viscosity and setback (i.e., the difference between the final viscosity at 30°C and the viscosity reached at the end of the holding period) were observed in the black rice (418 ±0.1 BU and 285 ±7.7 BU, respectively), followed by the red (587.5±3.5 BU and 385.5 ±4.9 BU, respectively) and brown (733±35.3 BU and 489.5±43.13 BU, respectively) rice.

Similar results have been reported by Lang et al. (2020), who attributed the differences in pasting properties in pigmented rice to differences in the phenolic compounds (Zhu, 2015). Indeed, the black rice used in this study was characterized by the highest SPAs (Fig. 1a) and TAC (Fig. 2). Phenolic compounds may compete with starch for water, thus affecting starch water absorption and gelatinization (Zhu et al., 2008), thereby resulting in a low viscosity. In addition, the hydroxyl groups of polyphenols may interact directly with starch, thus altering its properties (Zhu et al., 2008). During cooling, due to their ability to interact with both water and starch hydroxyl groups, phenolic compounds may limit starch interactions and thus its retrogradation (Zhu, 2015). Moreover, certain phenolic compounds may have a great ability to complex with amylose and/or proteins (Lang et al., 2020). Overall, the effect of these compounds on the pasting properties mainly appears to be dependent on the type of starch, the structure of the specific phenolic compound, and their capability to absorb water, as recently reviewed by Zhu (2015).

The pasting profile of the snacks (not shown here) indicated a total loss of viscosity after extrusion, irrespective of the type of rice, thus suggesting the loss of the crystalline order in starch granules. Similar results were obtained when extrusion was applied to various matrices, including corn (Bresciani et al., 2021).

3.6 Snack characteristics

So far, the interest in using pigmented rice for the production of snacks has almost exclusively concerned, although not in a systematic way, the optimization of the extrusion conditions and their effects on the phenolic profiles and/or antioxidant activity of the extrudates. Little attention has been paid to the physical characteristics of such snacks. In addition, the wide range of products – which are different in shape, size and structure - obtained from extrusion makes the comparison of the results with previous findings difficult. The present study has focused on a co-extruded snack, characterized by an outer shell that can be filled with either a savory or sweet filling. Since the filling needs to be contained within the snack, a compact structure is needed.

The features of the snack (i.e., section and inner area, porosity, bulk density and hardness) are shown in Table 1. The section area could be considered an index of the expansion degree, considering that the extruder die was not changed during the extrusion trials. Compared to the snacks from white rice, the section area and bulk density of those obtained when using brown rice decreased significantly. This result may be attributed to differences in the chemical composition of the rice samples (Supplementary Table 1). Indeed, the fiber content – thanks to its high water affinity - decreased the expansion capability (Dalbhagat et al., 2019). Lipids could act as an inhibitor by reducing the degree of gelatinization, thus reducing the expansion of snacks (Lin et al. 1997). Moreover, the high protein content – from the formation of intermolecular disulphide linkages as a result of the heat treatment – might reduce starch swelling and thus the expansion of extrudates (Dalbhagat et al., 2019). It was not possible to determine the porosity of the snacks made from the white rice because the macropores were larger than the measurement range. In addition, large pores were dissected by the cutter, thus creating open cavities that the instrument considered as non-pores.

When comparing the snacks from the brown, red and black rice, the highest section area and the lowest inner area were found in the brown rice samples, a result that is consistent with the lowest hardness value (Table 1). On the other hand, the biometric characteristics of the snacks made of red rice (i.e., low section area and high inner area) suggested a compact wall area (i.e., the part that separates the cavity from the outer wall) accounting for high resistance to breaking. The negative relationship between expansion capability (or section area) and hardness has already been shown (Bresciani et al., 2021; Robin et al., 2012). Similar hardness values to the control (white rice snack), together with a high inner area, make the red rice snacks ideal products for use on the co-extruded filled snack market. As far as porosity is concerned, the bulk density of all the samples increased as the value decreased. The black rice samples showed the highest porosity and therefore the lowest bulk density. Porosity makes a snack structure less resistant to breaking; indeed, this sample showed a low degree of hardness. Although the red and brown rice snacks showed similar porosity values, the bulk density was different. The red rice snacks recorded a lower bulk density than the brown rice snacks and resulted in a more compact structure, which was more resistant to breaking. This can also be noted from the section area values; the red rice snacks showed a lower degree of expansion and therefore a more compact structure than the brown rice snacks. Apart from the differences in chemical composition and starch properties, as well as the differences in kernel features might account for the differences in the snack characteristics. Indeed, it has been shown that rice obtained from varieties with a low length-breadth ratio (such as black rice, 2.1) undergo a greater expansion than products obtained from varieties with a higher length-breadth ratio (such as red rice, 3.7) (Gujral et al., 2002).

4 Conclusions

Pigmented rice could be a suitable raw material for the production of healthy and gluten-free co-extruded snacks. The comparison of white and brown rice of the same *cv* has indicated that the latter has a higher bioactive compound content and higher antioxidant activities. Although the final SPA and CWBPA contents in the pigmented and brown rice snacks did not differ, the red and black *cvs* both resulted in a higher AC. The black rice (*cv* Venere) was the rice richest in anthocyanins and also the one with the highest AC, even after extrusion. Furthermore, the higher phenolic compound content in pigmented rice may affect the pasting properties, and contribute to lowering the viscosity in raw-materials and increasing the porosity of the snacks, compared to brown rice. Considering both the biometric and textural properties, the best results were obtained when using red rice (*cv* Ermes).

Such information may be used successfully by industries interested in producing rice products which are rich in health-promoting phytochemicals. Optimizing the extrusion conditions for the production of snacks from pigmented rice will allow the loss of phenolic compounds to be reduced, the nutritional value to be increased and the physical properties of the snacks to be improved. However, the acceptability of such snacks by consumers still needs to be further investigated to better understand how the process can be modeled to satisfy the consumers’ needs.

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Figure captions

Figure 1.

Soluble phenolic acid (SPAs; panel A) and cell wall-bound phenolic acid (CWBPAs; panel B) contents of the raw material and snacks obtained from different rice cultivars.

Data are expressed on a dry weight basis. Bars with different letters are significantly different ($p<0.001$).

Figure 2.

Total anthocyanin content (TAC) in the raw material and snacks obtained from different rice cultivars.

Data are expressed on a dry weight basis. Bars with different letters are significantly different ($p<0.001$).

Figure 3.

Antioxidant capacity (AC), ABTS (panel A) and FRAP (panel B) assays in the raw material and snacks obtained from different rice cultivars.

Data are expressed on a dry weight basis. Bars with different letters are significantly different ($p<0.001$).

Figure 4.

Pasting profiles of the white, brown, red and black cultivars.

Figures

Figure 1.

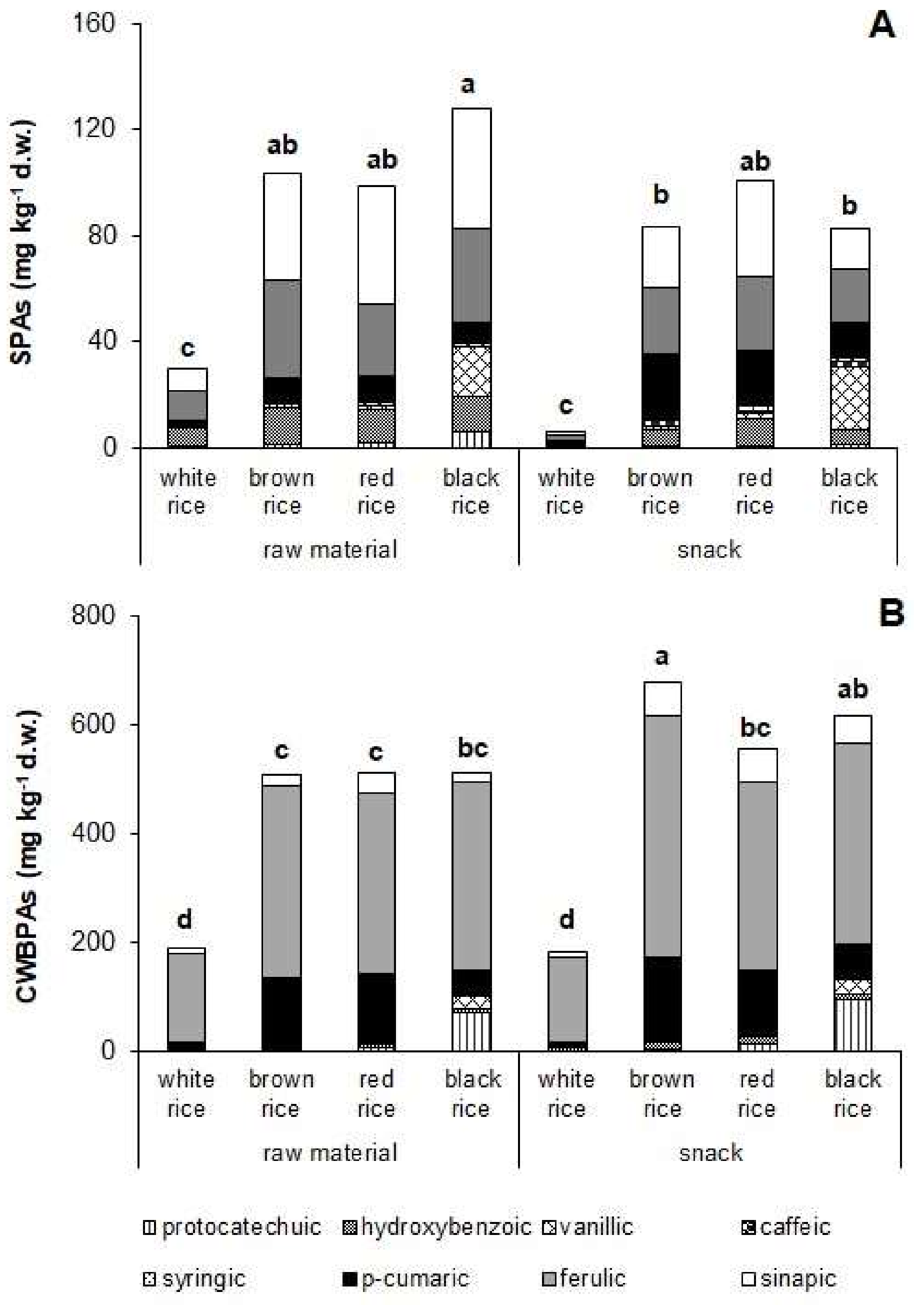


Figure 2.

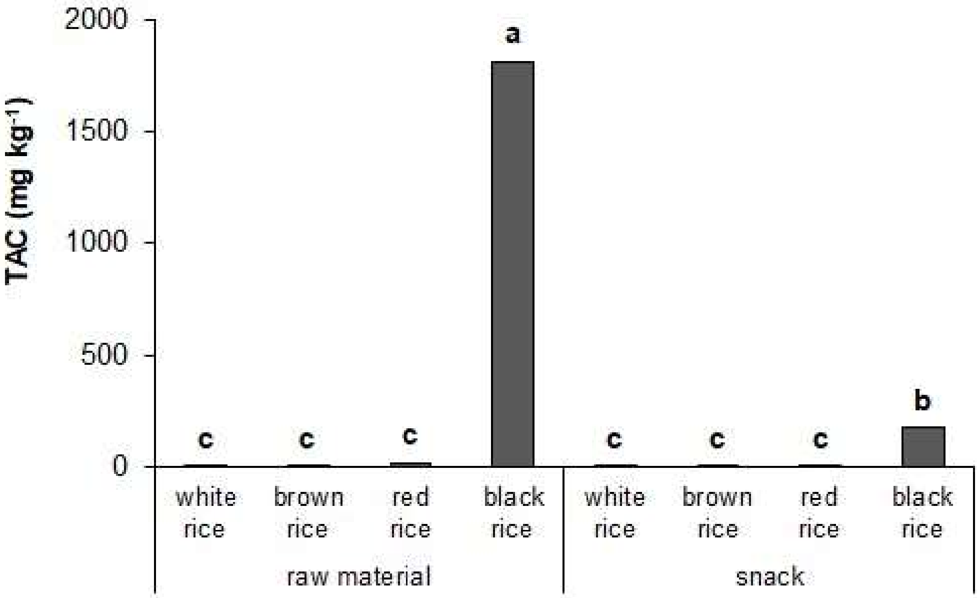

TAC (mg kg^{-1})
2000
1500
1000
500
0
a
b
c
c
c
c
c
c
white rice
brown rice
red rice
black rice
white rice
brown rice
red rice
black rice
raw material
snack

Figure 3.

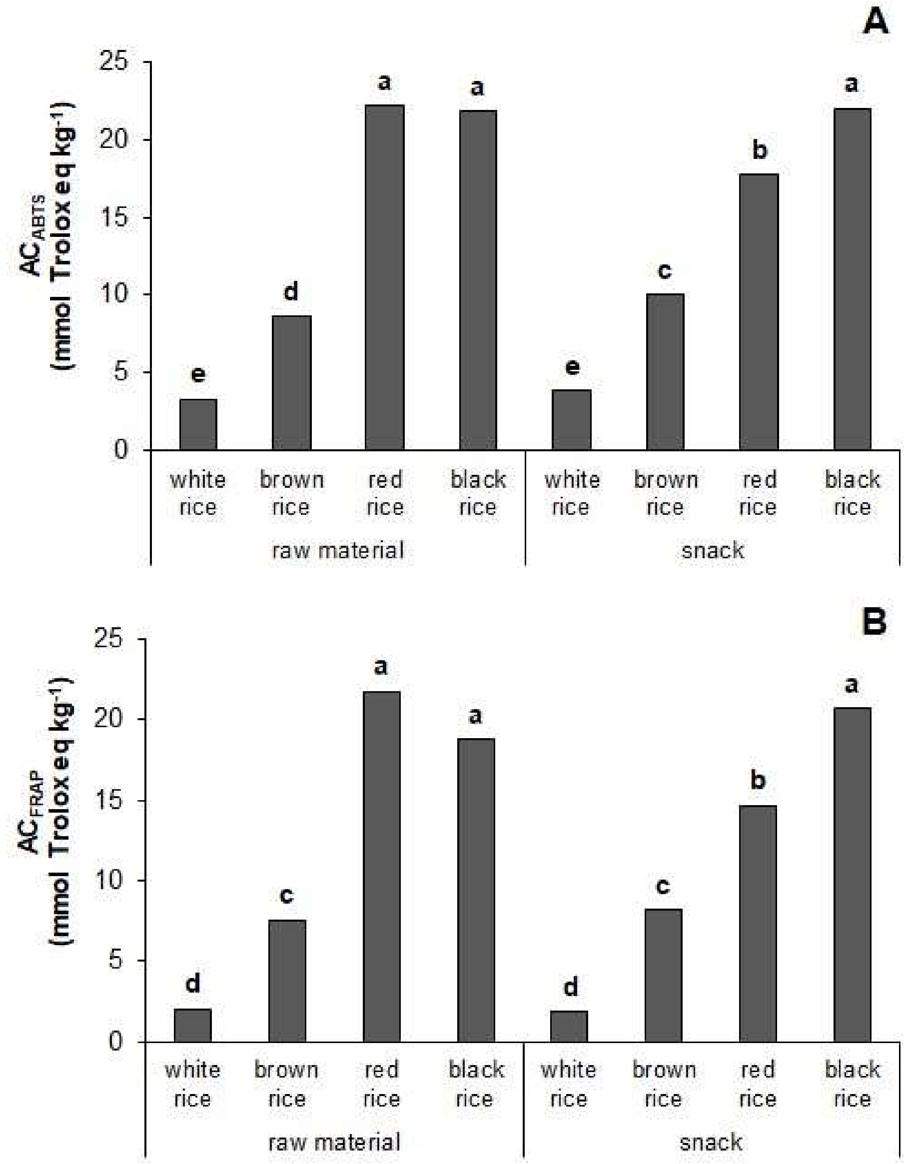
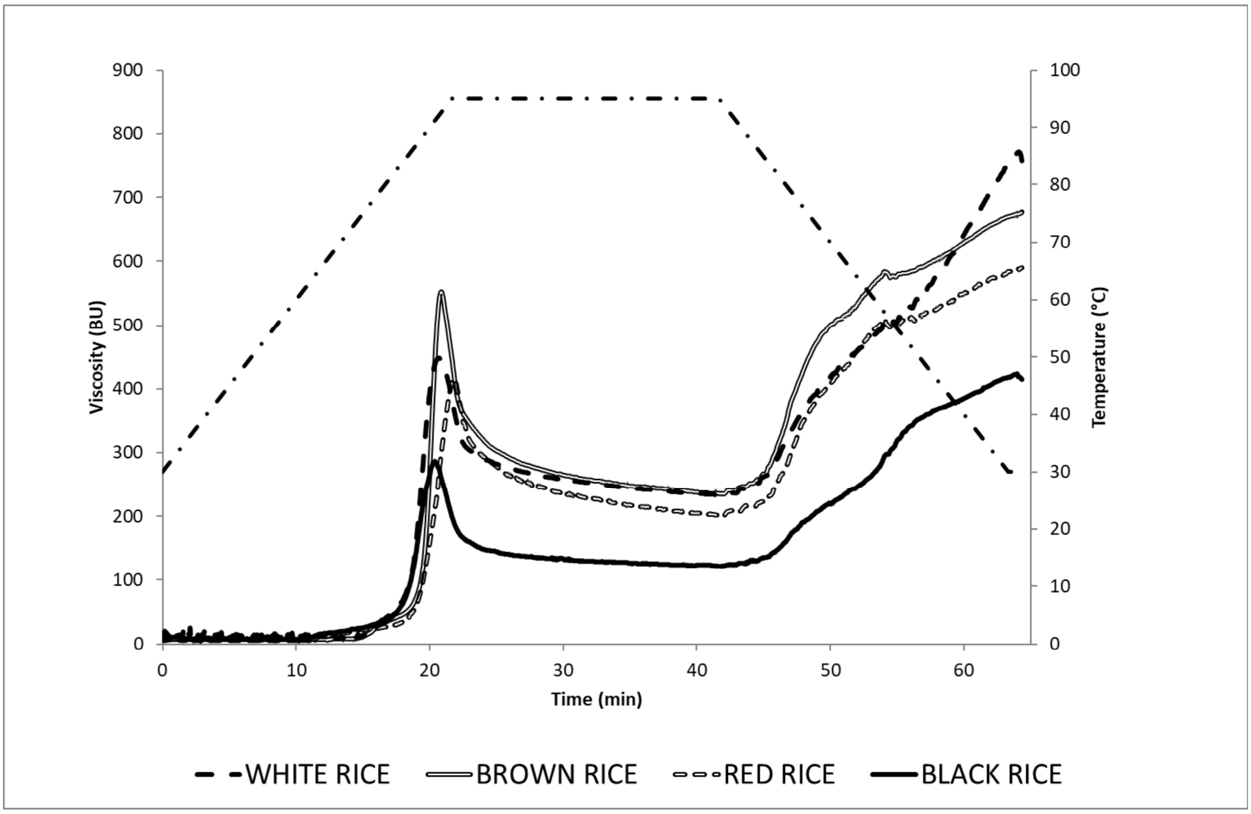

A
AC_{ABTS} (mmol Trolox eq kg^{-1})
25
20
15
10
5
0
e
d
a
a
e
c
b
a
white rice
brown rice
red rice
black rice
white rice
brown rice
red rice
black rice
raw material
snack
B
AC_{FRAP} (mmol Trolox eq kg^{-1})
25
20
15
10
5
0
d
c
a
a
d
c
b
a
white rice
brown rice
red rice
black rice
white rice
brown rice
red rice
black rice
raw material
snack

Figure 4.


Viscosity (BU)
900
800
700
600
500
400
300
200
100
0
Temperature (°C)
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
Time (min)
WHITE RICE
BROWN RICE
RED RICE
BLACK RICE

Tables

Table 1. Snack features of different rice *cvs.*

Parameters	White rice	Brown rice	Red rice	Black rice
Section area (mm^{2})	135.6^{a}	126^{b}	100^{c}	118^{bc}
Inner area (mm^{2})	15.3^{bc}	9.5^{c}	24.5^{a}	21.6^{ab}
Bulk density (gcm^{-3})	1.1^{a}	0.84^{b}	0.75^{c}	0.72^{c}
Porosity (%)	ND	45^{b}	47^{b}	56^{a}
Hardness (N)	46.3^{a}	35.1^{b}	43.9^{a}	36.9^{b}

Different letters in the same row are significantly different, according to the REGW-Q test ($p<0.001$).

The reported values are based on thirty replications for harness, ten replications for section area and inner area and two replications for bulk density and porosity. ND, not determinable