Chemical, Physical, and Sensory Properties of Bread with Popped Amaranth Flour

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This study investigated the effect of substitution of wheat flour with popped amaranth flour in bread formulation on the chemical, physical, and sensory characteristics of breads. The raw and popped amaranth grain flours of four Peruvian varieties: Oscar Blanco, Centenario, Taray, and Imperial, were characterised for chemical composition and pasting properties using Rapid Visco-Analyzer (RVA). Both types of amaranth flour had a high nutritional value, but the peak and final viscosity of popped amaranth flour were closer to the wheat flour. Breads were formulated with the popped amaranth flour, at four substitution levels of 0, 10, 20, and 30%. A significant increase in contents of protein (around 12%) and raw fiber (more than 100%), and a decrease in carbohydrate content (around 6%) in breads at the highest substitution level compared to wheat bread were observed. At this substitution level, the RVA profile parameters, specific volume, pore area, and colour coordinates (L*, a*, and b*) differed significantly. In the sensory analysis using Flash profile technique, consumers identified that the Taray and Imperial bread varieties at 10 and 20% substitution level were similar to the wheat bread. Adding popped amaranth flour to bread improved the nutritional value, ensuring good physical and sensory properties. Popped amaranth flour can, thus, be an alternative to wheat flour in the development of healthy bakery products.

Keywords: Amaranthus caudatus, popped grains, pasting properties, bread physical properties, Flash profile

INTRODUCTION

The genus Amaranthus is a pseudocereal from the Amaranthaceae family with more than 60 species. Only three species are used in the production of edible grains: Amaranthus hypochondriacus, Amaranthus cruentus, and Amaranthus caudatus [Kaur et al., 2010]. The most important Andean species is A. caudatus, cultivated in the Andes of Peru, Bolivia, Ecuador, and Argentina [Repo-Carrasco-Valencia et al., 2009]. Its grains have recently attracted interest for their high protein content (12.5–16 g/100 g) [Bressani et al., 1987]. Additionally, the amino acid profile of proteins is well-balanced in the context of human nutritional requirements [Drzewiecki, 2001], with the content of lysine, an amino acid with a high biological value, being two to three times higher than in other cereals, and a high content of methionine, cysteine, tryptophan, threonine, leucine and phenylalanine, which are the limiting amino acids in the protein profile of other cereals

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such as wheat [Bresani et al., 1987; Cotovaru & Mironesa, 2021; Palombini et al., 2013; Paucar-Menacho et al., 2018; Pavlik, 2012]. In addition, 100 g of amaranth grain contains between 7.7 to 12.8 g of lipids, which are rich in unsaturated fatty acids [Bresani et al., 1987]. Moreover, squalene, beneficial for human health, has a significant contribution to the lipid profile of amaranth [He et al., 2002; Venskutonis & Kraujalis, 2013]. It is a natural biosynthetic precursor of cholesterol and has photoprotective properties. The amaranth grains also contain high amounts of dietary fiber and minerals such as calcium and magnesium [Bodozra-Solarov et al., 2008]. They are also a rich source of nutrients; however, the presence of phytic acid, has adverse effects on the bioavailability of their minerals [Sanz-Penella et al., 2013].

The amaranth grain can be consumed roasted, popped, extruded, in flour, or as an added ingredient for bread, cakes, muffins, pancakes, cookies, dumplings, crepes, and noodles [Sanz-Penella et al., 2013]. Researches have demonstrated that the partial substitution of wheat flour with amaranth flour (5 to 20%) improves nutritional value and final sensory acceptance of breads [Cotovaru & Mironesa, 2021; Kamoto et al., 2018; Tomoskőzi et al., 2011]. Others studies have pointed out that a higher addition of amaranth flour to bread dough (greater than 40% substitution) not only improves the nutritional value of the product, but also allows the physical and sensory properties to be maintained at acceptable levels [Martinez et al., 2013; Miranda-Ramos et al., 2019; Rosell et al., 2009; Sanz-Penella et al., 2013]. Both raw and popped amaranth grain flour was used as a substitute for wheat flour in the bread preparation. Bodroza-Solarov et al. [2008] obtained a denser crumb structure, more uniform porosity, improved crust colour and great sensory acceptance of bread with popped A. cruentus grain flour at substitution level of 10–20% compared to wheat bread. Calderón de la Barca et al. [2010] produced gluten-free bread with up to 70% popped amaranth and 40% raw amaranth. They obtained acceptable physical characteristics of bread (loaves with homogeneous crumb and high specific volume) and rheological behaviour of the doughs, with a high nutritional value even without added hydrocolloids. Thus, popped amaranth could improve rheological and digestibility properties of breads since it is mainly composed of starches and proteins [Bodozra-Solarov et al., 2008]. Furthermore, the partial removal of the pericarp could reduce the content of antinutrients, such as phytic acid (IP6), since phytates are known to be concentrated in the bran of most cereals [Hama et al., 2011].

Several varieties of A. caudatus are cultivated in Peru, including Oscar Blanco, Centenario, INIA 414 Taray, and INIA 430 Imperial. This raised the interest in evaluating popped amaranth flour in various bread formulations. However, flours from popped grains of these varieties have not yet been studied in terms of addition to bread. Therefore, the objective of the present study was to compare the chemical and rheological properties of flour from raw and popped amaranth grains of four Peruvian varieties and evaluate the effect of the addition of popped amaranth flour on the chemical, physical, and sensory properties of bread.

**MATERIALS AND METHODS**

**Materials**

Grains of four Peruvian varieties of *Amaranthus caudatus* were used in study. The varieties Oscar Blanco (OB), INIA 414 Taray (T), and INIA 430 Imperial (I) were provided by Instituto Nacional de Innovación Agraria (INIA) station Andenes Cusco, Peru (harvest 2019). The Centenario (C) variety was acquired at UNALM, Lima, Peru (harvest 2019). The grain sizes of the four amaranth varieties used were as follows: Oscar Blanco – 1.1±0.18 mm, Centenario – 1.4±0.13 mm, Taray – 1.2±0.09 mm, Imperial – 1.3±0.12 mm. Wheat flour from “Los gallos mill” in Hermosillo, Sonora-México was used.

**Preparation of popped grain flours**

The amaranth grains were placed in a stainless-steel pot at 200°C for 15 s until complete popping was achieved [Amare et al., 2015; Bodroza-Solarov et al., 2008]. Subsequently, each variety of popped grain was pulverized in a disc mill, and the resulting flour was sieved through a 0.5 mm mesh, and identified as popped Oscar Blanco (POB), popped Taray (PT), popped Imperial (PI), and popped Centenario (PC). The flours were stored in polyethylene bags at 4°C until use.

**Dough preparation and baking**

The formulation for the control bread (with wheat flour) and the breads with 10, 20 and 30% substitution of wheat flour with popped amaranth flour are shown in Table 1. The solid ingredients were mixed and kneaded with water. Then the dough was placed in stainless steel molds, fermented at 40°C for 40 min, and baked at 150°C for 40 min. The loaves were cooled to room temperature (19°C), removed from the mold, and packed in high-density polyethylene containers.

**Proximate analysis**

The proximate composition of raw amaranth flours, popped amaranth flours and breads was analysed. The determinations were performed using the official methods of the AOAC International (AOAC, 2005). The contents of proteins (method 984.13), lipids (method 2003.05), ash (method 942.05), moisture (method 950.46), and raw fiber (method 962.09) were determined. Carbohydrate content was determined by subtraction of the total content of other constituents (expressed in g/100 g) from 100 g. Moisture determination for pasting profile analysis was performed using AACC International method 44-19 (AACC, 1995).

**Determination of pasting properties**

The pasting properties of the flours were analysed using the AACC International method 76-21 [AACC, 2000]. Wheat flour (WF), raw and popped amaranth flours, and blends of WF with popped amaranth flour (in proportion as in bred formulations) were analyzed on 3.5±0.01 g of sample adjusted to 14% moisture. The amount of water incorporated was 25±0.01 g, which was obtained from the flour adjustment [Shittu et al., 2007]. Rapid Visco-Analyzer (RVA, Super 4, Newport Scientific, Sydney, Australia) and Thermocline software (Newport Scientific) were used to

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TABLE 1. Formulations of breads without (control) and with the popped amaranth flour.

<table>
<thead>
<tr>
<th>Ingredient</th>
<th>Control</th>
<th>Substitution level (% of total flour)</th>
<th>10</th>
<th>20</th>
<th>30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheat flour (g)</td>
<td>300</td>
<td></td>
<td>270</td>
<td>240</td>
<td>210</td>
</tr>
<tr>
<td>Flour of popped amaranth (g)</td>
<td>0</td>
<td></td>
<td>30</td>
<td>60</td>
<td>90</td>
</tr>
<tr>
<td>Instant yeast (g)</td>
<td>8</td>
<td></td>
<td>8</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Brown sugar (g)</td>
<td>40</td>
<td></td>
<td>40</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>Vegetable shortening (g)</td>
<td>30</td>
<td></td>
<td>30</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Sodium chloride (g)</td>
<td>2</td>
<td></td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Water (mL)</td>
<td>170</td>
<td></td>
<td>Variable</td>
<td>Variable</td>
<td>Variable</td>
</tr>
</tbody>
</table>

obtain pasting profiles. An initial temperature of 50°C and mixing at 960 rpm were applied, decreasing the speed to 160 rpm after 10 s. The temperature was maintained at 50°C for 1 min and then increased to 95°C at 4.42 min, remaining until 7.42 min. At 11 min the temperature dropped to 50°C and the test ended at 13 min. The parameters recorded were pasting temperature, peak and final viscosities.

- **Bread specific volume determination**
  Volume of bread loaves (mL) was measured using laser topographic equipment (BVM-6610, Pertem Instruments, Sweden) and their weight (g) with analytical balance (Entris 224-1S, Sartorius Lab Instruments GmbH & Co.). The specific volume (mL/g) was calculated by dividing volume by weight [Vidaurre-Ruiz et al., 2019].

- **Bread porosity determination**
  Bread slices were photographed in colour using a camera. The images were scanned (Canon MG3610, Tokyo, Japan) at 600 dpi resolution, converted to gray colour, and processed with ImageJ software, version 1.51j8 (National Institutes of Health, Bethesda, MD, USA). The pixel values were converted into length units using dimensions of known lengths. The images were then binarized ( pores in black and crumb in white), determining the number of pores per cm² and the area percentage of the pores [Vidaurre-Ruiz et al., 2019].

- **Instrumental bread colour measurement**
  The bread colour coordinates were measured in the CIELab space using a CSM7 portable colourimeter (PCE instruments, Deutschland GmbH, Meschede, Germany). L* (0 – black, 100 – white), a* (positive value – red, negative value – green), and b* (positive value – yellow, negative value – blue) were recorded. Three points were measured for each bread slice [Yamsaengsung et al., 2010].

- **Flash profile sensory evaluation**
  For the sensory evaluation of bread, Flash profile (FP) technique was used, which is a descriptive sensory technique derived from the free-choice profile (each evaluator qualifies samples comparatively with their own words). Breads were evaluated in three sessions. In the first session, the samples were shown simultaneously and randomly, and the evaluators were asked to list sensory characteristics (attributes). The second session consisted of a consensus avoiding the repetition of two terms describing the same thing and then choosing their definitive list of attributes. In the third session, the samples were again presented simultaneously and randomly with a sensory evaluation of the chosen attributes. Finally, the evaluators were instructed to classify them in increasing order of intensities on an ordinal scale, allowing ties [Dairou & Sieffermann, 2002]. The information was analysed via a generalized Procrustes analysis (GPA). The evaluation was carried out with 24 evaluators (consumers) between men and women.

- **Statistical analysis**
  Data of nutritional composition and physical characteristics were expressed as mean and standard deviation and analyzed using the InfoStat free version 2017 software (InfoStat Group, Universidad Nacional de Córdoba, Argentina). The differences between treatments were established through the analysis of variance and Tukey multiple comparisons, considering statistically significant values of \( p < 0.05 \). Flash profile sensory evaluation data were evaluated by PGA with XLSTAT 2014 trial version software (Addinsoft, New York, NY, USA).

RESULTS AND DISCUSSION

- **Raw and popped amaranth flours and bread proximate analysis**
  The proximate composition of the flours of raw and popped amaranth grains of four varieties is shown in Table 2. Significant differences (\( p < 0.05 \)) between varieties were found in contents of protein (highlighting varieties I and T), lipids (highlighting the OB and C varieties), and ash (the highest content in flour of variety grains). No differences (\( p > 0.05 \)) were found in raw fiber and carbohydrate content in raw amaranth flour. The results were similar to those reported for *A. caudatus* [Alvarez-Jubete et al., 2009; Amare et al., 2016; Repo-Carrasco-Valencia et al., 2009] and *Amaranthus* spp. [USDA, 2019]. Table 2 also shows an increase in protein, fat, ash and a decrease in carbohydrate and raw fiber content in the four popped amaranth varieties compared to the raw samples. The protein contents in PI and PT were different (\( p < 0.05 \)) from the rest of the varieties; ash content was significantly higher (\( p < 0.05 \)) in PC than in POB and PT. No differences (\( p > 0.05 \)) between varieties were found in lipid, raw fiber, and carbohydrate contents. These data were consistent with findings from other studies for popped *A. cruentus* (increasing content compared to raw grains of lipids from 5.88 to 7.27% and soluble fiber from 8.61 to 9.22%) [Bodroza-Solarov et al., 2008] and popped *A. caudatus* var. Centenary (increasing content of total protein from 10.30 to 11.81 g/100 g dry weight and lipids from 7 to 8.17 g/100 g dry weight, decreasing content of carbohydrates from 80.3 to 70.15 g/100 g dry weight) [Paucar-Menacho et al., 2018].
Finally, Table 2 shows the proximate composition of breads with substitution in formula from 0 to 30% of wheat flour with amaranth popped flour of the four Peruvian varieties. As the percentage of WF substitution increased, the content of protein and raw fiber in bread showed an increasing tendency, while the content of carbohydrates – a decreasing one. The increase in the contents of protein and raw fiber and a decrease in carbohydrate content in breads with the highest substitution level compared to WF accounted for around 12%, more than 100% and around 6%, respectively. These trends were similar to those reported by Bodroza-Solarov et al. [2008], who made bread with popped A. cruentus at substitution levels of 10, 15, and 20%, resulting in higher contents of protein and crude fiber but a lower content of carbohydrates. Similar results were also reported for breads with raw flour of A. cruentus [Sanz-Penella et al., 2013], A. spinosus and A. hypochondriacus [Miranda-Ramos et al., 2019], A. hypochondriacus [Kamoto et al., 2018], and Ama- ranthus spp. [Cotovaru & Mironeasa, 2021] with substitution levels ranging from 5 to 50%. Moreover, a significant increase (p<0.05) in ash and lipid contents was observed in bread with popped amaranth flour compared to the control bread (with a few exceptions) (Table 2). These results agree with those reported in bread made from flours of popped A. cruentus (Bodroza-Solarov et al., 2008), raw A. cruentus (Sanz-Penella et al., 2013), and raw Amaranthus spp. (Cotovaru & Mironeasa, 2021). The improved nutritional properties of breads with popped amaranth flour can result from the favorable chemical composition of amaranth flour compared to wheat flour (higher protein and fiber content). A larger share of amaranth

<table>
<thead>
<tr>
<th>Flour/bread</th>
<th>Proteins (N x6.25)</th>
<th>Lipids</th>
<th>Raw fiber</th>
<th>Ash</th>
<th>Carbohydrates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw amaranth flour</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OB</td>
<td>13.45±0.29a</td>
<td>6.90±0.21a</td>
<td>3.89±0.12a</td>
<td>1.97±0.09a</td>
<td>73.79±0.47a</td>
</tr>
<tr>
<td>C</td>
<td>13.16±0.40b</td>
<td>6.64±0.00b</td>
<td>3.98±0.23b</td>
<td>2.35±0.04b</td>
<td>73.87±0.13b</td>
</tr>
<tr>
<td>T</td>
<td>14.9±0.20a</td>
<td>6.42±0.16b</td>
<td>4.25±0.09a</td>
<td>1.90±0.02a</td>
<td>72.53±0.43a</td>
</tr>
<tr>
<td>I</td>
<td>14.22±0.35ab</td>
<td>5.96±0.16b</td>
<td>3.76±0.19b</td>
<td>2.64±0.05b</td>
<td>73.42±0.74a</td>
</tr>
<tr>
<td>Popped amaranth flour</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>POB</td>
<td>14.59±0.07b</td>
<td>8.03±0.04a</td>
<td>3.58±0.17a</td>
<td>2.10±0.12a</td>
<td>71.7±0.16a</td>
</tr>
<tr>
<td>PC</td>
<td>14.08±0.03a</td>
<td>7.49±0.14a</td>
<td>3.08±0.39b</td>
<td>3.14±0.08a</td>
<td>72.21±0.57a</td>
</tr>
<tr>
<td>PT</td>
<td>15.25±0.15a</td>
<td>7.72±0.43a</td>
<td>2.87±0.10a</td>
<td>2.37±0.05b</td>
<td>71.79±0.33a</td>
</tr>
<tr>
<td>PI</td>
<td>15.54±0.15a</td>
<td>7.23±0.09a</td>
<td>3.24±0.08b</td>
<td>2.80±0.28ab</td>
<td>71.19±0.05a</td>
</tr>
<tr>
<td>Bread</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>11.35±0.82b</td>
<td>8.77±0.05a</td>
<td>0.53±0.04d</td>
<td>1.29±0.02bc</td>
<td>78.06±0.85a</td>
</tr>
<tr>
<td>POB10</td>
<td>12.96±0.12a</td>
<td>10.80±0.02bc</td>
<td>0.73±0.14cd</td>
<td>1.17±0.10a</td>
<td>74.36±0.39de</td>
</tr>
<tr>
<td>POB20</td>
<td>12.64±0.12a</td>
<td>9.07±0.07b</td>
<td>1.09±0.18bcd</td>
<td>2.04±0.02ac</td>
<td>75.16±0.32bc</td>
</tr>
<tr>
<td>POB30</td>
<td>12.74±0.34a</td>
<td>9.32±0.01c</td>
<td>1.27±0.03c</td>
<td>1.82±0.01bde</td>
<td>74.85±0.30cd</td>
</tr>
<tr>
<td>PC10</td>
<td>12.39±0.09ab</td>
<td>10.15±0.36bcd</td>
<td>0.78±0.02bc</td>
<td>1.48±0.25de</td>
<td>75.2±0.73bc</td>
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<tr>
<td>PC20</td>
<td>12.41±0.06ab</td>
<td>10.94±0.09b</td>
<td>1.05±0.24c</td>
<td>2.06±0.25bc</td>
<td>73.54±0.16ab</td>
</tr>
<tr>
<td>PC30</td>
<td>12.54±0.00ab</td>
<td>10.90±0.03a</td>
<td>1.36±0.17b</td>
<td>2.04±0.13abc</td>
<td>73.17±0.27a</td>
</tr>
<tr>
<td>PT10</td>
<td>12.29±0.21ab</td>
<td>10.60±0.04bc</td>
<td>0.86±0.00bcd</td>
<td>1.21±0.03b</td>
<td>75.05±0.22bcd</td>
</tr>
<tr>
<td>PT20</td>
<td>12.35±0.07ab</td>
<td>10.32±0.09abc</td>
<td>1.18±0.25bc</td>
<td>1.26±0.14bc</td>
<td>74.98±0.54bcd</td>
</tr>
<tr>
<td>PT30</td>
<td>12.36±0.06ab</td>
<td>9.49±0.19ab</td>
<td>1.53±0.01b</td>
<td>2.23±0.29a</td>
<td>74.39±0.03cde</td>
</tr>
<tr>
<td>PI10</td>
<td>12.26±0.10ab</td>
<td>9.97±0.17cde</td>
<td>0.97±0.18bcd</td>
<td>2.01±0.06abc</td>
<td>74.78±0.06bcd</td>
</tr>
<tr>
<td>PI20</td>
<td>12.29±0.54ab</td>
<td>8.69±0.08a</td>
<td>1.11±0.10cde</td>
<td>1.53±0.20cde</td>
<td>76.38±0.16bc</td>
</tr>
<tr>
<td>PI30</td>
<td>12.26±0.01ab</td>
<td>8.87±0.44g</td>
<td>1.32±0.25c</td>
<td>2.11±0.05b</td>
<td>75.44±0.22bc</td>
</tr>
</tbody>
</table>

Results are shown as mean ± standard deviation (n=3). Different letters in superscript in each column, separately for raw amaranth flours, popped amaranth flours and breads, represent significant differences (p<0.05). OB, Oscar Blanco variety; C, Centenario variety; T, Taray variety; I, Imperial variety; POB, PC, PT and PI, popped OB, C, T and I, respectively; POB10, POB20, POB30, PT10 and PT30, breads with 10% substitution of wheat flour with POB, PC, PT and PI, respectively; POB20, POB30, PT20, breads with 20% substitution of wheat flour with POB, PC, PT and PI, respectively; POB30, PC30, PT30, PI10, breads with 30% substitution of wheat flour with POB, PC, PT and PI, respectively.
in bread is beneficial not only because of its protein content, but also because of a high nutritional value of these proteins. Amaranth albumins and globulins are rich in essential amino acids, including lysine, and are easily digestible [Venskutonis & Kraujalis, 2013]. Moreover, according to the literature, heat treatment in popping of amaranth grains increases the protein efficiency ratio and the gelatinisation of starch positively affects the stability, strength and freshness of the crumb [Bodroza-Solarov et al., 2008]. Furthermore, it could affect protein digestibility due to the reduction of exogenous factors such as tannins, phytates, and trypsin inhibitors that reduce protein digestibility [Amare et al., 2015].

### Pasting properties
Parameters of the pasting profile of raw and popped amaranth flours and WF, including pasting temperature, peak and final viscosities, determined using RVA are show in **Figure 1A**. Pasting profiles show the flour viscosity changes during heating in excess water under constant agitation. The flour behaviours of raw and popped amaranth grain flours and WF showed significant differences \((p<0.05)\). A slightly higher pasting temperature was determined for raw amaranth flours than WF. However, the viscosity parameters of raw grain flours showed a considerably lower value. These results were similar, although slightly smaller differences were observed,

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**FIGURE 1.** Pasting characteristics of wheat flour (WF) and flours of raw and popped amaranth grains of four Peruvian varieties (A), and blends of FW with 10, 20 and 30% popped amaranth flour (B). OB, Oscar Blanco; C, Centenario; T, Taray; I, Imperial; POB, PC, PT and PI, popped OB, C, T and I, respectively. Results are shown as mean and standard deviation \((n=3)\). Different letters above bars indicate that the treatments are significantly different \((p<0.05)\).
to those reported in 11 lines of A. caudatus [Kaur et al., 2010] and A. hypochondriacus [Sindhu & Khatkar, 2016]. The pasting temperature was the lowest for flours of popped amaranth grains (Figure 1A). The other RVA profile parameters were also lower for popped grain flours than WF but higher than for raw grain flours. Our analyses showed lower values of pasting profile parameters than those reported for flours of raw and popped A. cruentus and A. hypochondriacus grains by Muyonga et al. [2014]. Popped samples would have better viscosity properties than raw amaranth flour because starch granules disintegrate during heating, becoming more susceptible to hydration, which is associated with increased viscosity [Lai, 2001] and possibly due to the impact of extreme dehydration when raw grain bursts [Muyonga et al., 2014].

Figure 1B also shows the differences in every RVA profile parameter of blends of wheat flour with popped amaranth flour of the four varieties used in bread formulation. The pasting temperature was higher (p<0.05) for the blends compared to WF; however, the proportion of WF and amaranth flour in the blend did not change pasting temperature significantly (p>0.05). In the rest of the viscosity characteristics, considerably lower values were found for blends than in the control flour and as the substitution level of WF with popped amaranth flour in the blend increased. These results were similar to the findings from a study of low-gluten bread made with amaranth flour, with substitution level of 0 to 40% [Duda et al., 2019]. It was found that as the substitution level increased, the peak and final viscosity were considerably reduced, and a slight increase in the pasting temperature was observed. Another study described bread with raw quinoa flour addition. The peak and final viscosity of the flours decreased slightly, while the dough temperature did not show differences as the substitution level increased from 0 to 20% [Vásquez et al., 2016]. In another study on pastes, in which wheat was substituted with A. hypochondriacus flour, the viscosity values were reduced as the substitution level increased up to 50% [Martínez et al., 2013]. This is possibly due to the low starch and amylose contents of the whole meal amaranth flour with respect to bread wheat flour. The grains with a low starch content swell and release amylose, resulting in a lower viscosity [Martínez et al., 2013]. Amaranth starch is characterised by a low amylose content from 4.7 to 12.5% [Kong et al., 2009] and a higher amylopectin content from 20 to 25% [Cotovanu & Mironeasa, 2022] affecting its functional properties [Kong et al., 2009]. Starch gelatinisation is a key factor in starch behaviour, which occurs when the dough is heated to 60°C. Low consistency values reached at the starch gelatinisation stage can be explained by the increased interactions between the low amount of amylose and the large length of amylopectin chain of amaranth starch, which generates a synergistic effect on the final viscosity and these on starch retrogradation [Corke et al., 2016; Piga et al., 2021]. This would indicate that the addition of amaranth flour could limit starch retrogradation and increase the shelf life of bread [Cotovanu & Mironeasa, 2022], but it would also contribute to the weakening of gluten [Sára & Dvořáček, 2017].

**Physical characteristics**

The physical characteristics of the breads with different levels of popped amaranth substitution from the four Peruvian varieties are shown in Table 3. Additionally, the appearance of bread cross-sections is shown in Figure 2. The breads POB10 and POB30 had lower weight compared to the others. The volume and specific volume decreased with the increase in the substitution of WF with popped amaranth flour in bread formulations. The WF bread presented the highest specific volume, although POB10, POB30 and PT10 did not differ significantly (p>0.05) from control in this respect. Our findings were consistent with the study by Bodroza-Solarov et al. [2008] who reported a reduction in the specific volume of bread by 33% when a 20% popped A. cruentus flour was used in formulation. Similar results were also obtained for amaranth flours of other species [Cotovanu & Mironeasa, 2021; Miranda-Ramos et al., 2019; Sanz-Penella et al., 2013; Tomósközi et al., 2011]. The reduction in the specific volume results from high-fiber ingredients [Iglesias-Puig et al., 2015]. This could also be explained by the dilution of gluten and decrease of α-amylase activity by globular proteins (11S and 9P) of amaranth, which reduces maltose availability for yeast during the bread-making process [Cotovanu & Mironeasa, 2021]. Whole-grain pseudoereal flours are high in dietary fiber but are gluten-free. However, proteins such as albumins and glutenins from WF can interact through disulfide bonds, maintaining the viscoelastic properties of gluten under acceptable conditions [Oszváld et al., 2009].

![FIGURE 2. Appearance of wheat flour (WF) bread and breads with 10, 20 and 30% substitution in formulation of WF with popped amaranth flours from four varieties including Popped Oscar Blanco (POB), Popped Centenario (PC), Popped Taray (PT), Popped Imperial (PI).](image-url)
Besides, a certain level of porosity, elasticity (glutenins) and viscosity, extensibility (gliadins), mixed with water, wheat proteins are hydrated, allowing the decrease in volume, porosity, and elasticity in formulations obtained in our research. On the other hand, the technological evaluation showed a higher number of cells with a lower specific volume and, for most amaranth varieties, a decrease in pore area (for flour from variety Imperial), an increase in pore area was determined with an increase in the share of flour in the bread formulation. A bread substituted with A. spinosus and A. hypochondriacus showed a higher number of cells/cm² as the substitution percentage increased [Miranda-Ramos et al., 2019]. In bread fortified with germinated Amaranthus sp. flour, the number of pores/cm² and the pore area also increased as the substitution increased [Guardianelli et al., 2021]. A bread formulation with 50% raw amaranth flour from A. spinosus and A. hypochondriacus showed a higher number of cells with a lower specific volume compared to control, but was found not significant [Miranda-Ramos et al., 2019]. It could be due to a loss of dough elasticity since low gluten availability. These results can be compared to those obtained in our research. On the other hand, the technological parameters significantly decrease compared to the control because of the weakening of the gluten network, which leads to a decrease in volume, porosity, and elasticity in formulations greater than 20% [Cotovano & Mironesa, 2021]. Since, when mixed with water, wheat proteins are hydrated, allowing the development of a dough with a balanced interrelation of cohesiveness, elasticity (glutenins) and viscosity, extensibility (gliadins), forming gluten network through S–S bonds and hydrogen bonding, retaining gas during fermentation and baking [Wieser et al., 2022]. The increased level of substitution results in a dilution of the protein fractions involved in gluten formation. Besides, the amaranth 11S proteins and globulin P are not enough to have a gluten network in the mixture, resulting in a softer dough [Cotovano & Mironesa, 2021].

**Sensory evaluation**

The bread samples of the 12 formulations were evaluated, including the control. Each consumer described between four to ten sensory attributes of their own, generating a total of 71 terms, subdivided into: general appearance (20), texture (29), aroma (05), colour (07), and taste (10). In addition, a consumer consensus index (RC) value of 0.61 (61%) was obtained, resulting in a positive correlation.

<table>
<thead>
<tr>
<th>Bread</th>
<th>Weight (g)</th>
<th>Volume (mL)</th>
<th>Specific volume (mL/g)</th>
<th>Number of pores per cm²</th>
<th>Pore area (%)</th>
<th>Colour coordinate (L°, a°, b°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>129.2±1.3a</td>
<td>487.00±16.97a</td>
<td>3.76±7.96a</td>
<td>60.00±2.20a</td>
<td>46.95±2.26abcd</td>
<td>74.96±1.23a</td>
</tr>
<tr>
<td>POB10</td>
<td>120.85±0.35ab</td>
<td>448.50±7.0ab</td>
<td>3.71±1.94ab</td>
<td>23.28±2.24ab</td>
<td>63.85±1.66ab</td>
<td>71.74±2.28ab</td>
</tr>
<tr>
<td>POB20</td>
<td>132.85±1.34a</td>
<td>417.00±12.72a</td>
<td>3.14±6.99abcd</td>
<td>33.06±2.12abcd</td>
<td>57.77±0.94abcd</td>
<td>69.89±1.08abcd</td>
</tr>
<tr>
<td>POB30</td>
<td>122.90±1.27ab</td>
<td>411.00±26.87ab</td>
<td>3.34±1.74abcd</td>
<td>78.61±1.46abcd</td>
<td>34.76±1.04abcd</td>
<td>61.94±0.96abcd</td>
</tr>
<tr>
<td>PC10</td>
<td>132.70±0.28a</td>
<td>429.50±7.3abc</td>
<td>3.24±7.30abcd</td>
<td>26.11±2.20abcd</td>
<td>52.04±1.38abcd</td>
<td>70.38±1.47abcd</td>
</tr>
<tr>
<td>PC20</td>
<td>134.50±2.26a</td>
<td>413.50±6.36bc</td>
<td>3.07±6.96c</td>
<td>48.89±0.31</td>
<td>27.74±4.05e</td>
<td>66.91±4.78ce</td>
</tr>
<tr>
<td>PC30</td>
<td>133.30±0.98a</td>
<td>396.50±7.0bc</td>
<td>2.97±1.25</td>
<td>75.94±4.32</td>
<td>29.40±3.35e</td>
<td>61.25±0.35e</td>
</tr>
<tr>
<td>PI10</td>
<td>131.10±1.4a</td>
<td>453.50±7.77ab</td>
<td>3.46±6.94abc</td>
<td>24.44±0.79ab</td>
<td>53.21±2.23d</td>
<td>69.49±1.11bc</td>
</tr>
<tr>
<td>PI20</td>
<td>134.65±0.07a</td>
<td>405.50±9.19bc</td>
<td>3.01±6.91cd</td>
<td>49.39±0.71abc</td>
<td>44.43±1.80abcd</td>
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<tr>
<td>PI30</td>
<td>131.85±0.35ab</td>
<td>372.50±9.49ab</td>
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<td>78.17±1.96</td>
<td>36.07±3.80abcd</td>
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<td>POB10</td>
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</tr>
<tr>
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<td>53.61±0.39cd</td>
<td>41.85±2.22bcde</td>
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<tr>
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<td>371.50±43.13a</td>
<td>2.82±58.84d</td>
<td>74.78±2.36</td>
<td>39.86±10.48abcd</td>
<td>58.84±0.84d</td>
</tr>
</tbody>
</table>

Results are shown as mean ± standard deviation (n=3). Different letters in superscript in each column, separately for raw amaranth flours, popped amaranth flours and breads, represent significant differences (p<0.05). POB, Popped Oscar Blanco; PC, Popped Centenario; PT, Popped Taray; PI, Popped Imperial; POB10, PC10, PT10 and PI10, breads with 10% substitution of wheat flour with POB, PC, PT and PI, respectively; POB20, PC20, PT20 and POB30, breads with 20% substitution of wheat flour with POB, PC, PT and PI, respectively; POB30, PC30, PT30 and PI30, breads with 30% substitution of wheat flour with POB, PC, PT and PI, respectively; L°, lightness; a°, redness–greenness; b°, yellowness–blueness.

**TABLE 3.** Physical characteristics and colour coordinates of breads without (control) and with popped amaranth flours.
The results of the Flash profile analysis (sensory attributes submitted by the consumers) were subjected into the GPA, which results are shown in Figure 3. The first two factors of GPA explained 65.86% of data variability (F1 = 52.94% and F2 = 12.92%). This value was lower than that reported for GPA of data for breads with raw A. hypochondriacus (86% variability) [Kamoto et al., 2018] and with germinated basul flour (72.99%) [Vilcanqui-Pérez et al., 2022]. The sample location in the sensory space is shown in Figure 3A. Four groups were evident in dimensions F1 and F2. Consumers identified the same sensory attributes within groups. The first group included the control and PT10, PI10, PT20 and PI20 samples, located in the positive areas of dimension 1 and negative ones of dimension 2. The second group included POB10 and PC10 samples, located in the positive areas of the two dimensions. The third group included POB20 and PC20, located in the negative zones of dimension 1 and positive of dimension 2. Finally, the fourth group comprised the treatments with the highest level of addition (30), located in the negative zones of the two dimensions. These results coincide with those reported by Kamoto et al. [2018] for breads with raw amaranth flour,
which were divided in GPA into three groups (breads with substitution levels 0–5%, 10–15, and 20–25) and by Vilcanqui-Pérez et al. (2022), showing similar attributes in three groups consisting of breads with 0%, 5-10%, and 15-20% of WF substitution with germinated basul flour. Figures 3A and 3B show the sensory space for samples and attributes, respectively. Sensory attribute differences are observed between groups. The first group (control, PT and PI, at 10 and 20% substitution) was characterised as fluffy, sticky, moist, light, and yeasty, with a soft crust and sweetness. Groups with PC10 and POB10 were described as buttery, sticky, astringent, soft, smooth, porous, and smelling like bread. Third group (PC20 and POB20) had attributes such as yeasty flavour, hardness, dryness, and gold. Finally, all the samples at 30% substitution were characterised as lumpy, small, not very fluffy, and with a dark crumb. Thus, PT and PI samples at 10 and 20% substitution were similar in their sensory profile to the control and showed the best attributes in taste and appearance. Descriptors found for bread with raw amaranth were crusts browning, alveolus size and regularity, earthy aroma, yeasty aroma, saltiness, sweetness, chewiness, crisp crust, elasticity, coarseness, crumb graininess, and stickiness (Kamoto et al., 2018). Attributes found in sprout basal breads were a sweet taste, sticky texture, and fluffy appearance (Vilcanqui-Pérez et al., 2022).

The higher addition of popped amaranth to bread affects the structure of the crust, elasticity, and crumb colour. Thicker cell walls and the grayish colour of the crumb are also observed, but uniform cells with thicker walls ensure higher breadcrumb stability and strength (Bodoza-Solarov et al., 2008). The lipid content of amaranth flour is six times higher than WF, hence, it can act as a surface-active agent and gas-stabilizing agent during baking, which could contribute to bread elasticity (Alvarez-Jubete et al., 2010).

CONCLUSIONS
Bread with 30% substitution of FW with popped amaranth flour had improved nutritional value with a lower carbohydrate content and higher protein and raw fiber contents compared to FW bread. The physical characteristics (peak and final viscosity, specific volume, pore percentage, and colour coordinates) showed reductions as substitution levels increased. According to the sensory evaluation, Taray and Imperial bread varieties at 10 and 20% substitution level were similar to the control with the best sensory attributes, specifically in taste and appearance. The results suggest that bread with popped amaranth flour could become a healthy alternative to wheat bread. However, further study on the phytate and mineral effect in bread is needed.

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CONFLICT OF INTERESTS
The authors declare that there is no conflict of interests.

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