Effect of micronization of high-fiber oat powder and vacuum-drying on pasta quality

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1. Introduction

A growing demand for functional foods such as high-fiber and low calorie products has been observed in recent years. Traditionally, pasta is made from durum wheat semolina, known to be a good source of low-glycemic index carbohydrates with low fat and sodium contents (Björk, Liljeborg, & Ostman, 2000; Brennan, 2008; Foschia, Peressini, Sensidoni, Brennan, & Brennan, 2015a). The Food and Drug Administration (FDA) considers pasta to be a good vehicle for nutrient fortification, and therefore several studies have been carried out aiming to enhance its nutritional value (Bustos, Perez, & León, 2011; Chillo, Laverse, Falcone, Protopapa, & Del Nobile, 2008; Krishnan, Menon, Padmaja, Sajeev, & Moorthy, 2012). As pasta is popular among consumers due to its easy preparation and long shelf life, incorporating dietary fiber into the traditional pasta recipe can contribute to increased dietary intake. However, the addition of dietary fiber to pasta influences not only its nutritional properties but also its functional properties, including color, texture, and cooking quality (Piwińska, Wywrisz, Kurek, & Wierzbicka, 2015b). The functional properties of dietary fiber can be altered by reduction of particle size (Chau, Wang, & Wen, 2007). Recently, the application of micronization in food research and technology has gained much attention. However, the effect of dietary fiber particle size on pasta quality has not yet been fully investigated. Chen et al. (2011) reported that the inclusion level and particle size of wheat bran affected the mixing characteristics and pasting properties of noodle flour, resulting in weakened mixing tolerance and increased premixing and cooking time. To our knowledge, no study has focused on the impact of the micronization of oat dietary fiber on pasta quality. Particle size reduction can allow an increase in the inclusion level of oat powder without adversely affecting the quality of the final product.

Pasta quality is largely affected by drying conditions. Currently, pasta is mostly manufactured with the use of high- and very high-temperature drying (Güler, Köksel, & Sarsılmaz, 2007). As pasta is popular among consumers due to its easy preparation and long shelf life, incorporating dietary fiber into the traditional pasta recipe can contribute to increased dietary intake. However, the addition of dietary fiber to pasta influences not only its nutritional properties but also its functional properties, including color, texture, and cooking quality (Piwińska, Wywrisz, Kurek, & Wierzbicka, 2015b). The functional properties of dietary fiber can be altered by reduction of particle size (Chau, Wang, & Wen, 2007). Recently, the application of micronization in food research and technology has gained much attention. However, the effect of dietary fiber particle size on pasta quality has not yet been fully investigated. Chen et al. (2011) reported that the inclusion level and particle size of wheat bran affected the mixing characteristics and pasting properties of noodle flour, resulting in weakened mixing tolerance and increased premixing and cooking time. To our knowledge, no study has focused on the impact of the micronization of oat dietary fiber on pasta quality. Particle size reduction can allow an increase in the inclusion level of oat powder without adversely affecting the quality of the final product.

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Ng, 2002). Dehydration at high temperature has been found to positively affect pasta quality, including reduced cooking loss and stickiness and greater firmness (Baiano, Conte, & Del Nobile, 2006; Zweifel, Handschin, Escher, & Conde-Petit, 2003). However, the lengthy times and high temperatures used during drying can promote oxidation, increase vitamin loss, and adversely affect the taste, aroma, and color (Bazyma et al., 2006). The pasta dehydration process must be carefully managed to allow uniform water removal and prevent the cracking that results from an excessive moisture gradient between the pasta core and its surface (Johnston, 2001; Marchylo & Dexter, 2001). During vacuum-drying, mass transfer is enhanced due to an increased pressure gradient within the product (Alibas, 2007; Péré & Rodier, 2002). Furthermore, reduced pressure decreases the boiling point of the solvent, leading to a lower required drying temperature (Durance & Wang, 2002). Compared with conventional air-drying, vacuum-drying has a higher drying rate, lower drying temperature, and can occur in an oxygen-deficient environment (Wu, Orikasa, Ogawa, & Tagawa, 2007). One previous study has indicated that drying conducted under reduced pressure had a favorable impact on the physical properties of pasta (Piwińska et al., 2015b).

The aim of this study was to investigate the effect of vacuum-drying, micronization, and enhanced level of high-fiber oat powder on pasta quality.

2. Materials and methods

2.1. Raw materials

Durum wheat semolina was supplied by Assmannsmühlen GmbH (Guntramsdorf, Austria). It contained 720 g/kg of carbohydrates, 130 g/kg of proteins, 12 g/kg of lipids, and 26 g/kg of dietary fiber. High-fiber oat powder was obtained from Microfood Poland Sp. z o.o. (Warsaw, Poland). It consisted of 800 g/kg of oat fiber (i.e. 780 g/kg insoluble and 20 g/kg soluble fractions), 40 g/kg of proteins, 32 g/kg of digestible carbohydrates, and 18 g/kg of lipids.

2.2. Micronization of high-fiber oat powder

High-fiber oat powder was micronized with the use of an Ultra Centrifugal Mill (ZM200, Retsch GmbH & Co., Haan, Germany) equipped with 0.5 mm sieve. Milling was performed at a speed of 14,000 rpm. To prevent excessive temperature increase, dry ice was used during the milling process.

2.3. Fraction separation

Fraction separation of high-fiber oat powder was performed with the use of a Vibratory Sieve Shaker (AS200, Retsch GmbH & Co., Haan, Germany) equipped with the following sieves: 0.425, 0.300, 0.150, 0.075, and 0.040 mm. Particles within the range 0.150–0.300 mm were referred to as coarse, 0.075–0.150 mm as medium, and below 0.075 mm as fine fiber fractions.

2.4. Particle size analysis

The particle size distribution of the obtained fractions of high-fiber oat powder was measured by the static automated imagining technique (Morphology G3S, Malvern Instruments Ltd, UK) and expressed as volume mean diameter. The measurements were performed in triplicate for coarse, medium, and fine fiber fractions.

2.5. Pasta preparation

Pasta was prepared with the use of durum wheat semolina, water, and high-fiber oat powder, the last of these being incorporated at two levels (100 and 200 g/kg). Pasta with no high-fiber oat powder included was referred to as the control. Semolina and oat powder were mixed for 1 min to ensure homogeneity of the dry ingredients. The mixture was hydrated with tap water (35°C) to 320 g/kg moisture and mixed for 10 min in a pasta machine (P3, La Monferrina, Italy). The dough was extruded through a bronze penne-forming die at a speed of 50 rpm. After extrusion, pasta was dried at high temperature (HT) in a drying oven (Binder, BINDER GmbH, Germany) and under reduced pressure in a vacuum-oven (VOS050, Mammert, Germany). HT drying technology consists of the following drying cycles: 60°C for 45 min, 65°C for 75 min, 67°C for 45 min, 65°C for 75 min, and then 62°C for 60 min. Vacuum-drying (VD) was conducted at 80°C in three 60 min cycles under reduced pressure (first 50 kPa, then 30 kPa, and finally 10 kPa). After drying, pasta was cooled to 35°C and stored in sealed bags at room temperature.

2.6. Total dietary fiber content

Measurement of total dietary fiber (TDF) was carried out on dried pasta samples according to the AOAC (2012) 2009.01 method, with the use of a FOSS Fibertec E 1023 system (Illerød, Denmark). Measurements were performed in triplicate.

2.7. Cooking quality

Cooking properties included swelling index, water uptake, and cooking loss, and these were evaluated after cooking 10 g samples in 300 ml of distilled water for one minute more than the optimal cooking time. Cooking time was determined according to the AACC approved method 66–50 (American Association of Cereal Chemists [AACC], 2000). Swelling index was evaluated according to the method described by Cleary and Brennan (2006). Water uptake was determined by the use of the method described by Petitot, Boyer, Minier, and Micard (2010). Cooking loss was expressed as a percentage of the starting material and was measured according to method described by Chillo et al. (2008). All measurements were performed in triplicate.

2.8. Color

The color of cooked pasta was determined instrumentally with the use of a Minolta Chroma Meter (Model CR-400, Konica Minolta Inc., Tokyo, Japan) with the L*a*b* measuring system (illuminant D65, 2° standard observer, measurement area □ 8 mm). The reference standard (L* = 98.45, a* = –0.10,
b* = −0.13) was used for white calibration. Values for L* (lightness), a* (− greenness, + redness), and b* (− blueness, + yellowness) were determined. Measurements were carried out at 10 measuring points for each sample.

2.9. Textural profile analysis

The textural properties of the cooked pasta were determined according to method described by Petitot et al. (2009), with the use of a Universal Testing Machine (Model 5965, Instron, MA, USA) equipped with a 35 mm cylindrical probe. After cooking (i.e. one minute longer than the optimal cooking time), the samples were allowed to equilibrate in a covered package. Samples were subjected to double compression until 70% of the initial thickness was reached, at a constant rate of deformation (2 mm/s). From the Texture Profile Analysis (TPA) curve, textural parameters of hardness, adhesiveness, and springiness were obtained. Measurements were repeated five times.

2.10. Statistical analysis

The data were statistically analyzed using multi-factor ANOVA. Statistica 10 for Windows (StatSoft Inc., Tulsa, OK, USA) was used for all statistical analyses.

3. Results and discussion

3.1. Particle size analysis

Table 1 shows the results of high-fiber oat powder particle size measurement. The initial average particle size of the high-fiber oat powder without micronization was 413.2 µm. After micronization, the oat powder was separated into coarse, medium, and fine fractions (average diameter 248.9, 141.2 µm, and 50.5 µm, respectively.

| Sample                  | Volume mean diameter [µm] |
|-------------------------|---------------------------|
| Without micronization   | 413.2 ± 11.0              |
| After micronization     |                           |
| Coarse (0.150–0.300 mm) | 248.9 ± 10.3              |
| Medium (0.075–0.150 mm) | 141.2 ± 8.6               |
| Fine (<0.075 mm)        | 50.5 ± 4.3                |

Means ± standard deviation (n = 3).

3.2. TDF content

The results obtained from the measurement of TDF are presented in Figure 1. TDF content increased with increased addition of high-fiber oat powder. The conventionally dried control sample was prepared from durum wheat semolina and contained 24.1 g/kg of TDF, while the vacuum-dried control sample contained 27.6 g/kg. When the content of high-fiber oat powder was increased to 200 g/kg, TDF values were enhanced to 140.2, 142.4, and 138.7 g/kg for conventionally dried pasta of fine, medium, and coarse particle size, respectively. TDF content in vacuum-dried samples with 200 g/kg of high-fiber oat powder was increased to 146.7 g/kg at the highest micronization level, 147.2 g/kg for the medium, and 146.2 g/kg for the lowest. Substitution of semolina with 100 g/kg of high-fiber oat powder enhanced TDF content to 76.8–83.1 g/kg, which is a level that permits the use of the ‘high in fiber’ nutritional claim label, as specified by Regulation (EC) No 1924/2006. Drying method and high-fiber oat powder particle size did not have any significant impact on TDF content.

3.3. Cooking quality

Table 2 shows the results of the cooking properties measurement. The optimal cooking time (OCT) of pasta was significantly longer in samples fortified with high-fiber oat powder.

Figure 1. Total dietary fiber content in pasta samples with high-fiber oat powder of fine, medium, and coarse particle size; conv – conventionally dried pasta, vac – vacuum-dried pasta; a–e Means with different letters are significantly different (P ≤ 0.05).

Figura 1. Contenido total de fibra dietética en las muestras de pasta con avena en polvo alta en fibra con partículas de tamaño fino, medio y grueso; conv – pasta secada convencionalmente, vac – pasta secada al vacío; a–e Los promedios con diferentes letras son significativamente distintos (P ≤ 0.05).
than for the control. An increase in OCT in pasta fortified with different combinations of dietary fibers was also reported by Foschia et al. (2015a).

The present results indicate that the drying method had a significant impact on the swelling index and water uptake: pasta samples dried in the vacuum-drier showed higher values compared with conventionally air-dried pasta. The obtained data are in line with a previous study (Piwińska, Wywirsz, Kurek, & Wierzbicka, 2015a) that also showed higher water absorption in samples dried under reduced pressure. Water uptake and swelling index were also influenced by particle size and addition levels of high-fiber oat powder: samples enriched with the oat powder showed higher values when compared to the control. The highest swelling index and water uptake were observed in pasta fortified with fine size high-fiber oat powder. Furthermore, both parameters increased with the addition of extra oat powder. Several studies have demonstrated that incorporation of dietary fiber into pasta recipes can result in higher water absorption compared with semolina pasta (Chillo, Brennan, Kuri, and Tudorica, 2012). Increased water absorption may be related with the strong water-binding ability of fiber (Chen, Rubenthaler, Leung, & Baranowski, 1988). The obtained data indicated that drying method, particle size, and addition level of high-fiber oat powder had a significant impact on cooking loss. This measured parameter’s value was the highest in conventionally dried samples fortified with 200 g/kg of coarse oat powder, while the substitution of semolina with 100 g/kg of fine powder resulted in the lowest cooking loss. Size reduction in the high-fiber oat powder resulted in a decrease in solid loss. Furthermore, cooking loss increased with an increased content of high-fiber oat powder. Reduced pressure during the drying process produced higher-quality pasta with lower cooking loss as compared with conventional air-dried pasta. All samples showed cooking loss values below 8% which, according to Dick and Youngs (1988), is the limiting value indicating high-quality pasta. Higher solid losses in pasta samples fortified with greater particle size and addition levels of high-fiber oat powder may be related to physical disruption of the gluten–protein network. As the gluten matrix is responsible for the integrity of pasta, the incorporation of non-gluten ingredients into a pasta formulation may have resulted in the interruption of structure continuity followed by greater solid loss during cooking (Khan, Yousif, Johnson, & Gamlath, 2013; Martinez, Ribotta, Añón, & León, 2013). Furthermore, greater cooking losses may be associated with the presence of water-soluble fractions of dietary fiber. Moreover, reduced particle size may result in better incorporation of high-fiber oat powder into the pasta structure and prevent excessive burdening. Increased cooking loss in pasta fortified with dietary fiber was also reported by Foschia et al. (2015a, 2015b). The obtained data in the present study are in line with Aravind et al. (2012), who observed increased solid loss with increased inulin addition. Kaur et al. (2012) studied the effect of varying cereal brans on the functional properties of pasta, and also reported that increased bran levels resulted in greater leaching of solids. Cooking losses of 8% or below are considered acceptable for good-quality pasta (Dick & Youngs, 1988).

Table 2. Calidad del cocinado de las muestras de pasta con avena en polvo alta en fibra con partículas de tamaño fino, medio y grueso secadas convencionalmente y secadas al vacío.

| Sample        | High-fiber oat powder [g/kg] | Drying method | OCT [min] | SI [g water/g dry pasta] | WU [g/100 g] | CL [g/100 g] |
|---------------|-----------------------------|---------------|-----------|-------------------------|--------------|-------------|
| Control       | 0                           | Conventional  | 7         | 1.32 ± 0.025            | 104.86 ± 1.293 | 2.90 ± 0.077 |
| Control       | 0                           | Vacuum        | 7         | 1.33 ± 0.025            | 110.25 ± 2.020 | 2.90 ± 0.048 |
| Fine          | 100                         | Conventional  | 9         | 1.50 ± 0.038            | 119.75 ± 1.961 | 2.53 ± 0.338 |
| Fine          | 100                         | Vacuum        | 10        | 1.57 ± 0.020            | 120.31 ± 2.617 | 2.22 ± 0.066 |
| Medium        | 100                         | Conventional  | 11        | 1.61 ± 0.035            | 124.44 ± 4.722 | 3.86 ± 0.826 |
| Medium        | 100                         | Vacuum        | 11        | 1.64 ± 0.034            | 125.32 ± 2.844 | 3.54 ± 0.087 |
| Coarse        | 100                         | Conventional  | 11.5      | 1.42 ± 0.014            | 118.25 ± 1.161 | 2.80 ± 0.046 |
| Coarse        | 100                         | Vacuum        | 9         | 1.42 ± 0.020            | 130.41 ± 2.725 | 3.53 ± 0.076 |
| Coarse        | 150                         | Conventional  | 13.5      | 1.46 ± 0.027            | 119.60 ± 1.279 | 5.18 ± 0.060 |
| Coarse        | 150                         | Vacuum        | 13        | 1.49 ± 0.027            | 124.89 ± 1.355 | 3.94 ± 0.070 |

Means ± standard deviations (n = 3); OCT – optimal cooking time, SI – swelling index, WU – water uptake, CL – cooking loss; ** – Means within a column with different superscripts are significantly different (P ≤ 0.05); ns – not statistically significant; *** – Means within a column with different superscripts are significantly distinct (P ≤ 0.05); ns – no es estadísticamente significativo, ** – p < 0.05; *** – p < 0.01.

Means ± desviaciones estándar (n = 3); OCT – tiempo de cocinado óptimo, SI – índice de hincharzón, WU – absorción de agua, CL – pérdida de volumen en el cocinado; ** – Los promedios en una misma columna con diferente superíndice son significativamente distintos (P ≤ 0.05); ns – no es estadísticamente significativo; ** – p < 0.05; *** – p < 0.01.
Table 3. Color measurement of conventionally and vacuum-dried pasta samples with high-fiber oat powder of fine, medium, and coarse particle size.

| Sample       | High-fiber oat powder [g/kg] | Drying method     | Color parameters |
|--------------|------------------------------|-------------------|------------------|
|              |                              |                   | L*               | a*   | b*  |
| Control      | 0                            | Conventional      | 68.7 ± 3.18      | -3.1*± 0.21 | 17.6***± 1.45 |
| Control      | 0                            | Vacuum            | 69.5± 1.67       | -3.4*± 0.20 | 17.6***± 1.36 |
| Fine         | 100                          | Conventional      | 57.5***± 1.87    | 1.6*± 0.37  | 17.7***± 1.31 |
|              | 100                          | Vacuum            | 59.7*± 1.82      | 1.6*± 0.19  | 19.3*± 0.42  |
| Medium       | 100                          | Conventional      | 49.1*± 3.89      | 2.9*± 0.27  | 18.0***± 0.85 |
|              | 100                          | Vacuum            | 52.7**± 2.36     | 2.4*± 0.20  | 18.9*± 0.45  |
| Coarse       | 100                          | Conventional      | 55.3***± 3.49    | 2.1*± 0.73  | 17.3***± 1.53 |
|              | 100                          | Vacuum            | 58.0***± 2.73    | 1.6*± 0.73  | 18.6***± 2.37 |
|              | 200                          | Conventional      | 54.8***± 2.03    | 3.0*± 0.34  | 17.3*± 0.98  |
|              | 200                          | Vacuum            | 56.6***± 1.80    | 2.5*± 0.49  | 18.1***± 1.10 |
|              | 200                          | Conventional      | 57.2***± 1.57    | 2.9*± 0.35  | 17.3***± 1.25 |
|              |                              | Vacuum            | 58.2***± 2.05    | 2.1*± 0.23  | 17.8***± 0.51 |
|              |                              | 200 Conventional  | 52.0*± 2.33      | 3.4*± 0.31  | 16.8*± 0.66  |
|              |                              | 200 Vacuum        | 54.1***± 2.39    | 2.7***± 0.39 | 17.5***± 0.70 |

Drying method effect  *** ns ***
Particle size effect  **** ns ****
Addition level effect *** ns ***
Drying method*Particle size effect ns *** ns
Drying method*Addition level effect ns *** ns
Particle size*Addition level effect *** ns ***
Drying method*Particle size*Addition level effect ns *** ns

Means ± standard deviations (n = 10); *** = Means within a column with different superscripts are significantly different (P ≤ 0.05); ns = not statistically significant; *P ≤ 0.05. **P ≤ 0.01. ***P ≤ 0.001.

Promedios ± desviaciones estándar (n = 10); *** Los promedios en una misma columna con diferentes superíndices son significativamente distintos (P ≤ 0.05); ns = no son estadísticamente significativos; *p ≤ 0.05. **p ≤ 0.01. ***p ≤ 0.001.

3.4. Color

The results of color measurement of cooked pasta are presented in Table 3. Pasta color is considered one of the key factors in determining consumer acceptance (Song, Zhu, Pei, AI, & Chen, 2013), and is primarily affected by the intrinsic quality of semolina and processing conditions (Borrelli et al., 2000). A bright yellow pasta color is most desired by consumers (Petitot et al., 2010).

Samples with added high-fiber oat powder showed significantly lower lightness as compared with the control. The L* value decreased with increased oat powder. Moreover, the results indicated that particle size had a significant impact on pasta lightness. Pasta with 100 g/kg of high-fiber oat powder showed the highest L* value for fine-size particles, while medium size was the most favorable size for pasta with 200 g/kg of high-fiber oat powder. Pasta lightness was also influenced by drying method. Vacuum-dried samples showed higher L* values compared with pasta dried by the conventional drying system. The data obtained are in line with the findings of Chillo et al. (2008), who reported a decrease in lightness in pasta fortified with buckwheat flour and bran. Similar results were obtained by Knuckles, Hudson, Chiu, and Sayre (1997), who investigated pasta fortified with barley β-glucan. Furthermore, Chen et al. (2011) studied the effect of particle size and addition wheat bran on the quality of dry white Chinese noodles, and reported that optimal lightness in dry dough sheets occurred with the smallest particle size of wheat bran. Our previous study also showed higher L* levels in vacuum-dried samples as compared with conventionally dried pasta (Piwińska et al., 2015a).

Pasta redness was significantly affected by both high-fiber oat powder content and particle size. The highest values of the a* parameter were observed in conventionally dried samples with 200 g/kg of high-fiber oat powder. Pasta yellowness was affected by drying method and the particle size of the oat powder. Samples fortified with fine sized high-fiber oat powder showed optimal yellowness. Vacuum-drying led to a more intense yellow color. Extra oat powder did not significantly impact the b* value. An increase in the a* value as a result of increased bran content was also reported by Chen et al. (2011). They also reported that the most intense red color in pasta occurred with the largest bran particle size.

3.5. TPA

The results of TPA are summarized in Table 4. Pasta hardness was affected by drying method, particle size, and extra high-fiber oat powder. Pasta dried under reduced pressure showed greater firmness when compared with samples dried by the conventional air-drying method. An increase in high-fiber oat powder caused a decrease in hardness; however, samples with 100 g/kg fine particles showed greater hardness compared with the control. Reduction in particle size resulted in an increase in pasta hardness. The highest firmness was observed in the vacuum-dried sample fortified with 100 g/kg of fine-size high-fiber oat powder. Similarly, the greatest adhesiveness was observed in pasta with 100 g/kg of fine-size pasta powder. Pasta springiness was not affected by drying method, or by high-fiber oat powder particle size or addition level. The results obtained are in accordance with Chen et al. (2011), who reported that the smallest particle size corresponded with significantly increased hardness as compared with the control, while the larger particle size was related to lower values of hardness. They also observed no impact of particle size and addition level on pasta springiness. It has been reported that coarse particle size and higher addition levels may have a greater impact on dough rheological properties and gluten network ( Özboy & Köksel, 1997; Zhang & Moore, 1997). Decrease in hardness may be attributed to the higher moisture content of cooked pasta fortified with high-fiber oat powder compared with control (Tudorica, Kuri, & Brennan, 2002).
Table 4. Medición de la textura de las muestras de pasta con avena en polvo con partículas de tamaño fino, medio y grueso secadas convencionalmente y con secado al vacío.

| Sample          | High-fiber oat powder [g/kg] | Drying method | Hardness [N] | Adhesiveness [J/cm²] | Springiness [-] |
|-----------------|------------------------------|---------------|--------------|----------------------|-----------------|
| Control         | 0                            | Conventional  | 2.11abc     | –0.0020d±0.0007      | 0.706±0.10      |
| Control         | 0                            | Vacuum        | 3.08def    | –0.0044e±0.0008      | 0.826±0.05      |
| Fine            | 100                          | Conventional  | 2.85de     | –0.0038ab±0.0009     | 0.726±0.17      |
| Control         | 100                          | Vacuum        | 3.43       | –0.0047±0.0007       | 0.786±0.06      |
| Fine            | 200                          | Conventional  | 2.05abc    | –0.0041ab±0.0005     | 0.816±0.03      |
| Control         | 200                          | Vacuum        | 2.69b      | –0.0030ab±0.0004     | 0.711±0.13      |
| Medium          | 100                          | Conventional  | 1.99b      | –0.0026a±0.0011      | 0.688±0.27      |
| Control         | 100                          | Vacuum        | 2.35bc     | –0.0033bc±0.0002     | 0.892±0.02      |
| Coarse          | 200                          | Conventional  | 1.52       | –0.0026c±0.0006      | 0.796±0.15      |
| Control         | 200                          | Vacuum        | 2.04ab     | –0.0028cd±0.0006     | 0.740±0.15      |
| Medium          | 100                          | Conventional  | 2.02abcd   | –0.0035abcd±0.0007   | 0.874±0.09      |
| Control         | 100                          | Vacuum        | 2.76abc    | –0.0041ab±0.0007     | 0.853±0.03      |
| Coarse          | 200                          | Conventional  | 1.54       | –0.0039abc±0.0005    | 0.811±0.10      |
| Control         | 200                          | Vacuum        | 2.59abc    | –0.0029abc±0.0003    | 0.653±0.30      |

Drying method effect

|                      | *** | ns | ns |
|----------------------|-----|----|----|
| Particle size effect  | *** | ns | ns |
| Addition level effect | **  | x  |    |
| Drying method*Particle size effect | ns | ns | ns |
| Drying method*Addition level effect | ns | ** | x  |
| Particle size*Addition level effect | ns | ns | ns |
| Drying method*Particle size*Addition level effect | ns | ns | ns |

Means ± standard deviations (n = 5); **†† Means within a column with different superscripts are significantly different (P ≤ 0.05); ns – not statistically significant; *p ≤ 0.05. **p ≤ 0.01. ***p ≤ 0.001.

4. Conclusions

Fortification of pasta with 100 g/kg of high-fiber oat powder increased total dietary fiber content to a level that permitted use of the ‘high in fiber’ nutritional claim. However, incorporation of non-gluten ingredients into pasta preparation caused significant changes in pasta quality. Extra-high-fiber oat powder led to increased water absorption and cooking loss, and decrease in both lightness and firmness. The use of micronization and vacuum-drying had a favorable impact on pasta quality. Reduction in oat powder particle size resulted in better cooking quality and physical properties of samples with 100 g/kg of semolina substitution. The pasta thus obtained showed a higher swelling index and water uptake yet lower cooking losses when compared with durum wheat semolina pasta. Furthermore, the sample with 100 g/kg of fine-sized oat powder showed the optimal firmness and lightness as compared with samples enriched with medium and coarse particles. Moreover, vacuum-dried pasta showed greater overall quality compared with conventional, air-dried samples.

The use of additives rich in dietary fiber to enrich pasta can result in increased dietary intake, while the use of innovative technologies including micronization and vacuum-drying can improve the overall quality of enriched pasta.

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