Effects of high energy milling on some functional properties of jicama starch (Pachyrhizus erosus L. Urban) and cassava starch (Manihot esculenta Crantz)

F. Martínez-Bustos a,*, M. López-Soto a, b, E. San Martín-Martínez c, J.J. Zazueta-Morales d, J.J. Velez-Medina a

a CINVESTAV, IPN, Unidad Querétaro, Libramiento Norponiente No. 2000, Fraccionamiento Real de Juriquilla, Apdo Postal 1-798, CP 76230 Querétaro, Qro., Mexico
b UACH—Departamento de Ingeniería Agroindustrial Universidad Autónoma Chapingo, 56230 Chapingo, Ed. de México, Mexico
c Instituto Politécnico Nacional, CICATA-Legaría, Mexico
d UAS Universidad Autónoma de Sinaloa, Posgrado en Alimentos, Apdo. Postal 1354, CP 82000, Culiacán, Sin, Mexico

Received 1 August 2004; received in revised form 27 July 2005; accepted 17 October 2005
Available online 28 February 2006

Abstract

In this study, the effect of high energy milling using a Spex ball mixer mill on some functional properties of cassava starch (Manihot utilissima) and jicama starch (Pachyrhizus erosus) were investigated. The properties of individual granules were strongly influenced by the high moisture of ball milling (friction and heat) and physicochemical properties of their amorphous and crystalline zones. High energy milling resulted in a partial fragmentation of the starch granules, increasing the water absorption index (WAI) and the water solubility index (WSI). Increasing moisture content the viscosity was decreased, attributable to the fragmentation of starch granules produced by the milling and favored by the increase of moisture content.

The crystallinity of cassava and jicama starches milled with high moisture contents and longer milling times was decreased. Thermal properties of both ball-milled starches were modified. The enthalpies were lower than native starch indicating that ball milling destroys the crystallinity and double helical order arrangements. Also, the resolution of the peaks was slightly decreased. Ball-milled jicama and cassava starches showed some functional characteristics of gelatinization that possibility their use in food systems as stabilizing, additives, moisture retainers and thickeners.

© 2006 Elsevier Ltd. All rights reserved.

Keywords: Ball mill; Cassava; Jicama; Starch

1. Introduction

The properties of native starches do not meet the standards necessary for a wide range of industrial uses (paper, textile, foods, plastic, etc.). However, native starch granules can be modified to obtain the desired properties. Chemical modification (such as oxidation, hydrolysis, cross-linking, and/or acetylating) is most often used, but there is a growing interest in the physical modification of starch (microwave, ultraviolet, radiation, ohmic heating, moisture or shearing), especially for food applications. These physically modified starches are considered to be very safe natural materials (Jacobs & Delcour, 1998).

Jicama (P. erosus L. Urban) belongs to the family Leguminosae, subfamily Papilionoidea. This leguminous plant has species native from the Amazon region and from
2. Materials and methods

2.1. Raw materials

Two Mexican tubercle species were used: cassava (*M. iihot esculenta* Crantz) from Veracruz state, Mexico and Jicama (*P. erosus* L. Urban) from Guanajuato state, México.

2.2. Isolation and sample preparation of starch

The cassava starch (C) was isolated following the method of Defloor, Dehing, and Delcour (1998). Jicama starch (J), was isolated following the method reported by Galván-Mendoza et al. (2001). Roots were washed and cut in small fragments. The samples were wet milled in a stone mill and submitted to wet sieved and the suspension was centrifuged. The recovered starch was washed and dried. Jicama and cassava native starches showed pH of 7 and 6.33, respectively. Jicama starch samples (Y) were neutralized before processing, using solutions of NaOH 0.1 N to reach a pH of about 7. This sample was named Jn.

A pulverizer/mixer ball mill (Spex model 8000, SPEX CertiPrep, Inc., Metuchen, NJ, USA) was used. It consists of an arm that moves in three axial directions to shake a stainless steel container containing the hermetically sealed sample. Samples of 20 g of starch, steeped to achieve the desired moisture content (Table 1), were placed into the container together with 11 iron balls covered with Ni–Cr measuring 1/2 in. in diameter. The mixer mill shook the container with the sample in three perpendicular directions at approximately 1200 rpm during the milling time specified in the experimental design (Table 1). The milling container had an internal volume of 50–60 ml and a capacity of 25 ml. After examining the data found for WAI, WSI and viscosity characteristics, the samples selected for further analyses of crystallinity and thermal properties were J3, J5, J7, C1, C6, C9.

2.3. Water absorption index (WAI) and water solubility index (WSI)

These parameters were determined using the method of Anderson (1982). WAI was reported as grams of water/grams of dried sample and the WSI reported as percentage. The moisture content was determined by using AACC method No. 44–19 (AACC, 1995).

2.4. X-ray diffraction and crystallinity

The X-ray diffraction patterns were taken by a Carl Zeiss diffractometer operating at 35 kV with Cu K radiation. The diffractograms were recorded from 2° to 35° on the 20 scale. The sweeping angle was from 5° to 50° with a speed of 4.5°/min. The percentage of crystallinity was defined as the ratio of the area under the crystalline diffraction peaks to that of the non-coherent diffracted intensity. The
non-coherent intensity was obtained by subtracting the sharp diffraction peaks from the total diffraction intensity. The crystallinity was normalized to that of the raw starch, which was assumed to be 100% (Rodríguez et al., 1995). Two determinations were made for each sample.

2.5. Pasting properties

A Rapid Visco Analyzer (RVA-3D, Newport Scientific Pty, Australia) was used to measure the apparent viscosity of the samples (AACC, Method 61-02, 1995).

2.6. Damaged starch

The iodine reaction was evaluated using spectrophotometric procedures (Williams & Fegol, 1969). The damaged starch value was expressed in Farrand equivalent units (FEU), using the regression equation

\[ X = 0.286 + 5.30Y \]

where \( X \) = FEU and \( Y \) = absorbance value. The Farrand units were related to the percentage of damaged starch (% DS) using the expression

\[ \text{FEU} = \left( \frac{5.2 \times \text{DS}}{C} \right) / 10.3, \]

where DS is the damaged starch. So,

\[ \text{DS} = \left( \frac{\text{FEU} + 10.3}{5.2} \right)^{-1}. \]

2.7. Thermal properties

Differential Scanning Calorimetry (DSC 822e Mettler Toledo Lab Plant Birefrigerated, Huddersfield, England) was used applying the method described by Xu and Seib (1993). The heating cycle was modified, following the indications of Wang, White, and Pollak (1993), to 40–100–100–30 °C. The weight of the samples was 2.3 mg (10% moisture content). The gelatinization percentage of the samples with respect to native starch was calculated using the following equation:

\[ \text{Gelatinization} \ (\%) = \left( \frac{\Delta H_G \text{ raw starch} - \Delta H_G \text{ milled starch}}{\Delta H_G \text{ raw starch}} \right) \times 100. \]

2.8. Experimental design and data analysis

All treatments were performed randomly and the data were analyzed using response surface methodology with SAS (1992). Statistical Analytical System. Release 6.08. SAS Institute Inc., Cary, NC. The significance of the models was tested using the variance analysis (F test) and the \( R^2 \) value. The effect of the variables was registered using surface graphs. An experimental design with two variables and five levels of variation for moisture content and the milling time were included (Table 1). A central composite rotatable design (Montgomery, 1991) was used for the pulverizer/mixer ball mill process, consisting of 13 assays with five repetitions at the central point, four factorial points and four axial points. The experimental data were fit to a second order model. The mathematical model was

\[ Y = b_0 + b_1X_1 + b_2X_2 + b_{11}X_1^2 + b_{22}X_2^2 + b_{12}X_1X_2, \]

where \( Y \) is the response, \( X_1 \) is the moisture content (%), \( X_2 \) is the milling time and \( b_0, b_1, b_2, b_{11}, b_{22}, \) and \( b_{12} \) are the regression coefficients.

3. Results and discussion

3.1. Water absorption index (WAI) and water solubility index (WSI)

The values of WAI for jicama starch at 50 °C varied from 2.46 to 3.83 g/g. Raw starch and neutralized starch showed values of 2.46 g/g and 2.53 g/g, respectively (Table 1).
2). The highest WAI values at 50°C were for the J6 and J3 samples. Sanguanpong et al. (2003) reported values from 0.5 to 3.0 g/g of swelling power during starch hydrolysis and ball milling of cassava starch.

The highest WAI at 80°C was found in the J4 and J6 samples, with values of 12.69 and 10.72 g/g, respectively. The rest of the samples had values between 7.29 and 9.84 g/g. These values were lower than those reported by Martínez-Bustos, López-Soto, Zazueta-Morales, and Morales-Sánchez (2005), who reported values for the WAI at 50°C ranging from 3.16 to 4.47, and from 7.29 to 8.96 for the WAI at 80°C for pregelatinized jicama starch using ohmic heating. The WSI at 50 and 80°C increased the hydrosoluble fraction considerably; some of the highest values were obtained for J3, J4 and J6. These samples partially disintegrated at higher temperatures, thus increasing the WSI values. Martínez-Bustos et al. (2005) reported a maximum value of 2.16 for the WSI at 50°C and 1.94 at 80°C for pregelatinized jicama starch using ohmic heating. Swelling of small-particle and fragmented starch was accompanied by the solubilization of water-soluble fragments at temperatures above 50°C. However, the WSI at 80°C of J4 and J6 was lower than at 50°C probably due to high moisture content during ball milling decreasing the hydrosoluble fraction. In most of hydrated samples the WAI increased with increasing temperature and ball milling (mechanical damage and local heat) as expected even though the granules were broken as indicated by an increasing WSI values. However, these functional properties were strongly influenced by the hydration level, ball milling time, and structure and origin of starch granules. The values of WAI at 50°C for cassava starch varied from 2.67 to 4.05 g/g (Table 3), and those found for jicama starch varied from 3.21 to 3.83 g/g.

The C4 and C8 samples of cassava starch showed an increase in their WAI at 50°C of approximately 65% in comparison to raw starch, also, all the WAI values at 80°C were increased. The WSI at 50°C increased from 1.062% (raw starch) to 15.73% and 14.95% for C4 and C6, respectively. Samples C2, C3, and C0 showed higher values of WSI at 80°C than those found at 50°C. High friction energy caused fragmentation in the starch granules, thus increasing the WSI values. High energy milling involves movement in three orthogonal directions which produces a collision geometry that leads to particle fragmentation, with different types of fractures depending on the impact angle (Maurice & Courtney, 1990). In aqueous systems, the suspension offers resistance to the trajectory of the milling elements and the speed of collision is reduced. Milled starch granules lose their ordered structure, suffer-

<table>
<thead>
<tr>
<th>Trials</th>
<th>Variables</th>
<th>Moisture (%)</th>
<th>Time (min)</th>
<th>WAI (g/g) 50°C</th>
<th>WSI (%) 50°C</th>
<th>WSI (%) 80°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>J1</td>
<td></td>
<td>55</td>
<td>10</td>
<td>3.21</td>
<td>7.64</td>
<td>3.48</td>
</tr>
<tr>
<td>J2</td>
<td></td>
<td>55</td>
<td>20</td>
<td>3.31</td>
<td>8.74</td>
<td>5.37</td>
</tr>
<tr>
<td>J3</td>
<td></td>
<td>65</td>
<td>10</td>
<td>3.69</td>
<td>6.99</td>
<td>12.60</td>
</tr>
<tr>
<td>J4</td>
<td></td>
<td>65</td>
<td>20</td>
<td>3.26</td>
<td>12.69</td>
<td>7.71</td>
</tr>
<tr>
<td>J5</td>
<td></td>
<td>52.9</td>
<td>15</td>
<td>3.23</td>
<td>7.29</td>
<td>3.02</td>
</tr>
<tr>
<td>J6</td>
<td></td>
<td>67.1</td>
<td>15</td>
<td>3.83</td>
<td>10.72</td>
<td>10.75</td>
</tr>
<tr>
<td>J7</td>
<td></td>
<td>60</td>
<td>7.9</td>
<td>3.21</td>
<td>8.02</td>
<td>5.20</td>
</tr>
<tr>
<td>J8</td>
<td></td>
<td>60</td>
<td>22.1</td>
<td>3.61</td>
<td>9.84</td>
<td>9.68</td>
</tr>
</tbody>
</table>

| J(9–13) |           | 60           | 15         | 3.62           | 8.53        | 5.44        | 8.53        |
| J0     |           | –            | –          | 2.46           | 8.49        | 1.14        | 8.49        |
| Jn     |           | –            | –          | 2.53           | 8.46        | 1.01        | nd          |

nd, not determined; Jn, neutralized jicama starch; WAI, water absorption index; WSI, water solubility index.
ing different degrees of damage. High WSI values indicate the presence of greater amounts of soluble substances. Thus, the Hi-Energy Mill leads to granule fragmentation with capacity for solubilization or suspension in the water for an extended period.

3.2. Pasting properties

Maximum viscosity at 90 °C of jicama starch (JV90) fitted to a mathematical model, showed a significant variance \((p < 0.0012), p < 0.05\) level of probability, and \(R^2 = 0.916\).

\[
JV90 = 46232.3185 - 1100.82612MC - 920.96421MT + 6.47566MC^2 + 2.07177MT^2 + 13.82MC \times MT,
\]

where MC, moisture content; MT, milling time.

Fig. 1 shows the fitted model of JV90 for this response. Fig. 1a indicates that JV90 decreased with the increasing of moisture content for the selected interval of milling time. Thus, the high viscosity (JV90) was found with the lowest milling condition (8 min) and 52% moisture content. These results indicate that for these conditions the most of the granule integrity was conserved. Increasing the moisture contents the viscosity was decreased, attributable to the fragmentation of starch granules produced by the milling and favored by the increase of moisture content. Viscosity values at 50 °C during the cooling cycle (Table 1) fitted to a mathematical model, had a significant variance \((p < 0.0008), p < 0.05\) level of probability, and a determination coefficient of \(R^2 = 0.925\).

\[
JV50 = 73715.05541 - 1986.44129MC - 1038.45867MT + 13.81248MC^2 + 6.11559MT^2 + 13.77MC \times MT,
\]

where MC, moisture content; MT, milling time.

This behavior was similar to these found at JV90, thus, the moisture content had a significant effect in the decreasing of viscosity (Fig. 1b). However, comparing the viscosity values of JV90 and JV50 (Table 1) it is observed that some of JV50 values were greater than JV90, except the trials of 9, 11, 12 and 13. However, all the CV50 were smaller than CV90. Attributed to the specific conditions of moisture content and milling time that slightly decreased the JV50.

The viscosity of raw jicama starch (JV90) and (JV50) were 3293 and 3997 cP, respectively, higher than most of the ball-milled starches, indicating that the milling process produces the fragmentation of the starch granules decreasing the viscosity values.

Viscosity values of cassava starch at 90 °C (Table 1) fitted to a mathematical model, had a significant variance \((p < 0.0061), p < 0.05\) level of probability, and a determination coefficient of \(R^2 = 0.810\).

![Fig. 1a. Viscosity profile at 90 °C (JV90) of milled jicama starch.](image1)

![Fig. 1b. Viscosity profile at 50 °C (JV50) of milled jicama starch.](image2)
The maximum viscosity values of cassava starch at 90 °C (CV90) were found to the lowest milling conditions (52% moisture content and 8 min, milling time), similar to raw cassava starch indicating that in these conditions there was not a considerable fragmentation of starch granules. Increasing the moisture content and maintaining constant the milling time the viscosity was decreased. Also, the increasing of milling time decreased CV90 (Fig. 2). However, as the moisture content was increased, the fragmentation of granules was increased decreasing the viscosity values. Also, this effect was found for high milling time, attributable to the mechanical friction and the energy (local heat) generated during the process. CV50 (Table 1) showed not significant variance (p > 0.1468), indicating that the factors of variation in the selected levels not affected the viscosity at 50 °C. In all the assays the values of CV50 were lower than those of CV90 which indicate that the cassava starch had a low retrogradation, similar to raw cassava starch. Jicama starch was more susceptible to ball milling with lower values of JV50 than cassava starch, probably due to the smaller proportion of amylopectin (73%) and higher relative crystallinity (27%) in comparison with cassava starch (86% and 17%), respectively (Alvarado et al., 1996; Galván-Mendoza et al., 2001; Melo, Krieger, & Montenegro, 1994).

### Table 4

<table>
<thead>
<tr>
<th>Trials</th>
<th>Variables</th>
<th>Moisture content (%)</th>
<th>Milling time (min)</th>
<th>DS (%)</th>
<th>RC (%)</th>
<th>Response variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>J0</td>
<td>Raw starch</td>
<td>–</td>
<td>2.13a</td>
<td>–</td>
<td>54.60–66.67</td>
<td>61.65</td>
</tr>
<tr>
<td>J3</td>
<td>65</td>
<td>10</td>
<td>6.26d</td>
<td>83.41</td>
<td>56.35–70.13</td>
<td>60.63</td>
</tr>
<tr>
<td>J5</td>
<td>52.93</td>
<td>15</td>
<td>3.69c</td>
<td>91.02</td>
<td>59.04–67.17</td>
<td>62.69</td>
</tr>
<tr>
<td>J7</td>
<td>67.07</td>
<td>15</td>
<td>7.93</td>
<td>86.76</td>
<td>54.86–66.31</td>
<td>57.37</td>
</tr>
<tr>
<td>Jn</td>
<td>60</td>
<td>15</td>
<td>2.30a</td>
<td>–</td>
<td>57.73–69.27</td>
<td>–</td>
</tr>
<tr>
<td>C0</td>
<td>Raw</td>
<td>–</td>
<td>2.33c</td>
<td>–</td>
<td>58.28–70.83</td>
<td>63.14</td>
</tr>
<tr>
<td>C1</td>
<td>55</td>
<td>10</td>
<td>3.90a</td>
<td>84.92</td>
<td>58.00–68.75</td>
<td>62.40</td>
</tr>
<tr>
<td>C6</td>
<td>67.07</td>
<td>15</td>
<td>7.07b</td>
<td>67.85</td>
<td>58.27–68.75</td>
<td>62.46</td>
</tr>
<tr>
<td>C9</td>
<td>60</td>
<td>15</td>
<td>7.35b</td>
<td>78.96</td>
<td>56.34–68.15</td>
<td>62.41</td>
</tr>
</tbody>
</table>

Treatments in the same group were not different significantly, test of Tukey (α = 0.05). DS (%), damaged starch; RC (%), relative crystallinity = crystallinity of milled sample (%)/crystallinity of raw starch (%); Tc–Te, onset and conclusion temperatures; Tp, peak temperature; ΔHg, gelatinization enthalpy; G, gelatinization in relation to raw starches (%).
and is the type found in cereal starch, although it is also found in some roots and tubercles like potatoes, cassava and yams (Takeda, Tokunaga, Takeda, & Huizuri, 1986). The lowest crystallinity values were for raw cassava starch (27.39%). Zobel (1988) reported 38% crystallinity in native cassava starch with 18% amylose. In both starches crystallinity decreased in all ball-milled samples (Table 4). Jicama starch samples with high moisture content and intermediate milling time showed significant decreasing in the crystallinity values (x = 0.05) in comparison to raw jicama starch. The J3 sample milled to the highest moisture content (65%) showed the lowest values for crystallinity, corroborating the previous affirmations. The crystallinity of cassava starch milled with high moisture content and longer milling times decreased 6.5% in comparison to raw starch. Also it was observed that increases of moisture contents during milling produce greater loss of crystallinity (C6). Sanguanpong et al. (2003) reported that ball milling promoted molecular disorder and decreased crystallinity. Similar to this values these authors found 23.5%, 16.5% and 14.0% of relative crystallinity, respectively, for native cassava starch and for samples that were ball milled for 2 and 3 h. The molecular orientation (i.e., double helices) remained relatively similar to that of the native starch, resulting in no observable change in the X-ray diffraction pattern of both ball-milled starches (data not shown). In general, the characteristic peaks of both types of starches were conserved, however, their resolution decreased slightly (data not shown). The ordered three-dimensional structure of the amylopectin segment is responsible for the crystallinity of starch granules, whereas the amylose segments form the dominant amorphous area (Zobel, 1988). The loss of peak resolution (widening and reduced altitude) reflects decreasing crystallinity and an increase in the amorphous component of the structure. A partial loss of crystallinity in ball milling is to be expected, and this is caused by a rise in the temperature due to conduction or dissipation of the mechanical energy during ball milling. Sanguanpong et al. (2003) reported that milled native cassava starch was highly amorphous. Although hirnerization led to higher crystallinity, subsequent ball milling caused a loss of crystallinity.

3.5. Thermal properties

Raw jicama starch required higher energy to achieve complete gelatinization (10.45 J g⁻¹) than did cassava starch (8.30 J g⁻¹). This is attributable to the source of the starch (Table 4). Jn showed a ΔH_G of 9.70 J g⁻¹. For both starches onset, peak, and conclusion temperatures were decreased after ball milling. Sanguanpong et al. (2003) reported similar values for ball-milled 1, 2 and 3 h native and cassava starch. Native starch granules started to show some enlargement at temperatures above 54 °C and were fully enlarged at >66 °C. The swelling of the granules started before the gelatinization onset temperature (T_s ≈ 61 °C) and the granule expansion peak for jicama starch occurred around the gelatinization peak temperature (T_p ≈ 61.65 °C). Similar results were found by Alvarado et al. (1996) and Galván-Mendoza et al. (2001) who reported changes in the gelatinization enthalpy of ΔH_G (J g⁻¹) of 4.92 and 10.71 for raw jicama starch (starch–water ratio = 1:2). For cassava starch, the values reported for ΔH_G were 4.8 (J g⁻¹) (Hoover, 2001) and 15.7 (Xu & Seib, 1993), with starch–water ratios of 1:2 and 1:3, respectively, in the gelatinization temperature range of 62–84 °C.

The cassava starch samples C6, C9, and C1 showed a degree of gelatinization of 40.0%, 18.79% and 11.52%, respectively (Table 4). T_p was lower for both ball-milled starches (except for J5 and C1). The enthalpies were lower in both starches than those for native starch, indicating that ball milling destroys the crystallinity and double helical order arrangements.

Samples of ball-milled jicama starch (J3) and ball-milled cassava starch (C6) milled with the highest moisture content showed the greatest change during ball milling (G %). J3 showed a degree of gelatinization 41.62%, followed by J5, with 22.96% and J7 with 16.75%. The cassava starch samples C6, C9, and C1 showed a degree of gelatinization of 40.0%, 18.79% and 11.52%, respectively (Table 4). In pregelatinized starches prepared with mild conditions (without cutting force to swollen grains) the amylose fraction is partially solubilized by leaching, and the starch components are slightly degraded and probably they follow connected within a continuous matrix. Thus, these products show a high accessibility to water and limited cold water solubility (due to the high components of molecular weight), disperse easily in cold water to form moderately stable suspensions and can mainly be used in food and textile industry (Bonazzi et al., 1996).

T_p was lower for both ball-milled starches (except for J5 and C1). The enthalpies were lower in both starches than those for native starch, indicating that ball milling destroys the crystallinity and double helical order arrangements.

3.6. Microphotographs of jicama starch

Fig. 3a and b showed jicama starch milled with high moisture content. When the starch granules disperse, they swell and absorb the available water, and, as result they become more susceptible to mechanical fragmentation. Mechanical damage is a transformation from an ordered to a disordered (amorphous) structure via the breakage of intermolecular bonds. The microphotographs show swollen and fragmented granules, including the proportion of damaged starch. Fragmented and intact granules, when gelatinized, adhere to others forming a matrix that facilitates the interaction between granules, thus increasing viscosity allowing their reassociation when cooling. The starch granules contained more defects or weak points, allowing fracture and breakage into smaller particle sizes. The results are in agreement with earlier reports on acid hydrolysis and ball milling of corn starch (Niemann & Whistler, 1992). Jane et al. (1992) reported that the particle
size after ball milling was proportional to the average starch molecular size of the samples.

Fig. 4a and b shows scanning electron micrographs of cassava starch milled for 15 min with a 67.07% moisture content. Broken starch granules, depicting the granular mechanical damage are observed. Extensive milling broke the particles into smaller fractions, appearing as wedge shapes. The granular structure of ball-milled native starch appeared to be broken (irregular in shape) but still clustered with the original granule remnants. The morphology after ball milling changed considerably, which could have a significant impact on functional behavior, e.g., rheological properties. Broken pieces that are in smaller fragments contribute to the amorphous domains, some of which become solubilized during heat/moisture treatment. Local heat generated during milling can cause crystallinity loss and the development of molten, highly viscous liquids (cement).

4. Conclusions

Ball milling considerably increased the hydro soluble fraction of both starches. The functional properties were strongly influenced by the moisture content and milling time. In both starches the moisture content during milling has a significant effect in the fragmentation of starch granules producing modifications in the water absorption and solubility indexes, viscoamilograph profiles, endothermic broadening effect and crystallinity. The granular structure of ball-milled native starch appeared to be broken but still dispersed among the original granule remnants. The morphology after ball milling was considerably changed, which had a significant impact on the functional properties of both starches. Ball-milled starches showed some functional properties that may be of potential use in the food industry.

Acknowledgement

Research support was provided by the Consejo Nacional de Ciencia y Tecnología (CONACYT, Mexico) (Proyecto No. 37782-B).

References


