ACTA Acta Sci. Pol. Technol. Aliment. 21(1) 2022, 91–99
www.food.actapol.net pISSN 1644-0730 eISSN 1898-9594 http://dx.doi.org/10.17306/J.AFS.2022.1006

ORIGINAL PAPER

Received: 16.10.2021
Accepted: 3.01.2022

EVALUATION OF MICROWAVE HEATING ON THE MECHANICAL PROPERTIES, β-GLUCAN, AND FIBER CONTENT OF BARLEY KERNELS

Patricia López-Perea[1]✉, Juan de Dios Figueroa-Cárdenas[2], Alma Delia Román-Gutiérrez[3], Fabiola Araceli Guzmán-Ortiz[4], Elba Ronquillo-de Jesús[1]

[1]Área de Ingeniería Agroindustrial, Universidad Politécnica de Francisco I. Madero
Domicilio Conocido, Tepatepec, Francisco I. Madero, Hidalgo, **México**
[2]Centro de Investigación y de Estudios Avanzados (CINVESTAV-Unidad Querétaro)
Libramiento Norponiente 2000, Fracc. Real de Juriquilla, Querétaro, **México**
[3]Área Académica de Química, Universidad Autónoma del Estado de Hidalgo
Carretera Pachuca-Tulancingo Km. 4.5, Ciudad del Conocimiento Mineral de la Reforma, Hidalgo, **México**
[4]Cátedras CONACyT. Área Académica de Química, Universidad Autónoma del Estado de Hidalgo
Carretera Pachuca-Tulancingo Km. 4.5, Ciudad del Conocimiento Mineral de la Reforma, Hidalgo, **México**

ABSTRACT

Background. Microwave heating may affect some non-starch polysaccharides of cereal kernels. This microwave effect can be positive for functional properties and the final product. Therefore, the purpose of this work was to explore the effects of microwave heating on mechanical properties, malt extract yield, wort viscosity, β-glucan of wort, and soluble, insoluble, and total dietary fiber in malting and feed barley.
Material and methods. The barley kernels were microwave heated for 4 and 8 s and compared with a control (0 s) with no microwave irradiation treatment. The mechanical properties were measured by compressive loadings; an Environmental Scanning Electron Microscopy was used for kernel layers. β-glucan content in the barley kernel and wort was measured with a Mixed Linkage beta-glucan (K-BGLU Megazyme International; Wicklow, Ireland). Insoluble, soluble, and total dietary fiber was determined using 32-07 of AACC method.
Results. The thickness of barley kernel bran layers was related to the mechanical properties. The modulus of elasticity decreased after 4 s of heating but increased after 8 s. Irradiation affected non-starch polysaccharides, such as β-glucan and fiber. β-glucan decreased after 4 s as did wort viscosity. The insoluble and total dietary fiber followed the same trend as β-glucan, but the soluble fiber content increased with prolonged microwave heating.
Conclusions. A few seconds of microwave heating is enough to increase barley's value in the brewing industry and improve health benefits due to minor changes in the biochemical grain components.

Keywords: malt, wort, modulus of elasticity, barley, microwave, irradiation

INTRODUCTION

The industrial and domestic use of microwaves has increased dramatically over the past few decades. While the use of large-scale microwave processes is increasing, recent improvements in the design of high-powered microwave ovens have reduced equipment manufacturing costs. In agriculture, the energy of microwaves has been used to dry or to warm freshly harvested corn, to control fungal counts, and

✉plopez@upfim.edu.mx, https://orcid.org/0000-0002-3603-788X

to condition wheat kernels (Dolinska et al., 2004). López-Perea et al. (2008; 2011), reported the use of microwave heating to increase the extract yield and malting quality of feed and malting barleys. Microwave irradiation is an available alternative to chemical fumigation for the significant reduction of grain damage by insect pests (Warchalewski et al., 1998). Few reports describe the use of microwave technology in grain processing; neither has this technology been taken advantage of in terms of its potential to improve grains and seeds (López-Perea et al., 2008; 2011). In contrast, trends in electrical energy costs offer significant potential for developing new and improved industrial microwave processes (Vadivanbal and Jayas, 2007).

Recently, the demand for dietary fiber by the food market has sparked interest in feed barley around the world due to the high β-glucan content in bran and endosperm. This interest arises from the evidence that β-glucan is an essential supplement in human nutrition that reduces the risk of cancer and diabetes and assists in the prevention of obesity and cholesterol levels (Pino, et al., 2021; Roudi et al., 2017; Schlörmann and Glei, 2017). Rose et al. (2010) indicated that the benefits of barley β-glucans are related to concentration within the grain and the processing conditions that may affect the extractability and molecular weight. In this context, microwave energy can modify the kernel endosperm in seconds and increase the industrial quality of grains. Therefore, it is interesting to study the effect microwave irradiation has on β-glucans and dietary fiber of barley. The main advantage of microwaves is a fast and selective heating ability compared to conventional heating methods. When applying microwave radiation to reduce the kernel moisture content or control insects or other applications, researchers should always consider how this treatment will affect wheat grain properties (Grundas et al., 2008). Research on the direct effects of microwave-induced changes in barley kernel endosperm remains an essential and exciting issue.

The purpose of this study is to investigate possible changes in the malting quality, β-glucans, dietary fiber, and physico-chemical properties of microwave-irradiated barley grains.

MATERIALS AND METHODS

Materials

Two barley varieties were used: feed barley (Pastor Ortiz) and malting barley (Esmeralda) grown in Hidalgo, Mexico, and harvested in 2019.

Cleaning and selection of grain

For every sample of barley, 5 kg was run through four sieves; two had circular orifices with diameters of 12/64 and 6/64 inches, to separate the impurities from the barley kernels. The clean grain was then selected according to size by using two sieves with oblong orifices of 6/64×3/4 inches, and 5.5/64×3/4 inches (Seedburo Equipment Company, Des Plaines, IL), based on Official Norm NMX-FF-043-SCFI-2003 (2003).

Environmental Scanning Electron Microscopy (ESEM)

Five barley kernels were placed into a rubber disk mold. The kernels were embedded into acrylic resin: methyl methacrylate and 2-hydroxyethyl methacrylate (AcryFix, Struers, Denmark). The sample was allowed to rest for 12 h before being removed from the rubber mold. Longitudinal sectioning of the kernel structures was performed by mounting the samples on a Struers Rotopol-25 polishing tool and subsequently using various polishing pads to polish until the surface appeared shiny. Finally, a clean cloth piece of cotton was used for final polishing and cleaning before the observation. Additionally, if required, slices (pastilles) may be cut using a precision table cutting machine (Accutom-5, Struers, Denmark) equipped with a diamond blade disk for precise and deformation-free cutting on both sides, assuring a parallel shape of the pastille (Figueroa et al., 2011).

For the bran morphology, an ESEM model XL30 (Phillips, Research Laboratories, Eindhoven, The Netherlands) equipped with a beam of 20 kV GSE or BSE detectors was used. Micrograph images were taken at 350X, 1 Torr, and a spot size of 4.5 to record the bran layers in the curved dorsal region of the grains at their maximum height.

Irradiation with microwaves

A conventional microwave oven (model R-501CW, Sharp Electronics Corp., Mahwah, NJ) with a power capacity of 1.45 kW and a frequency of 2,450 MHz was used. The microwave oven was calibrated following the method of Khraisheh et al. (2004), and the kernel samples (100 g, dry basis) were placed in 2 kg polyethylene bags. The samples were arranged in layers one or two grains thick, avoiding conglomerates to achieve homogeneous irradiation. The electromagnetic irradiation exposure times that did not affect the germination for malting and less than 38°C were 4 and 8 s, according to López-Perea et al. (2008), and were used a control time of 0 s.

Mechanical properties

Compression force, modulus of elasticity, stress, and strain of the barley kernel were determined. Then the following methodology was used: kernel width, height, and size were measured using a digital caliper (model CD-6 CS, Mitutoyo, Japan). A TA-XT2 texture analyzer (Texture Technologies Corporation, Stable Micro Systems, Surrey, England) was used to measure the kernel response to compressive loadings between two parallel plates (an aluminum probe 10 mm in diameter × 8.3 in height with a base of 15×15 mm and the plate). To determine the contact area (load-bearing area) in individual kernels during the loading process, an ink pad was first used to paint the kernel; they were taped onto the loading face of the top plate to record the ink impression contact surface of the grain during loading. After compression, the contact mark left by the grain represented the actual contact area. The impression was then digitalized, and the area was calculated using IMAGE-J software. Before loading, the height of each kernel was determined with a caliper. Individual kernels were placed onto the plate with the crease side down (Ponce-García et al., 2008).

Malting

Steeping. Samples (100 g, db) of irradiated barley were placed in the germinating chamber (Seedburo Equipment EU650) at 16°C for 48 hr, having reached 45% grain moisture.

Germination. The samples were placed in the same germinating chamber at 16°C and 100% RH in darkness for four days.

Kilning. This step was carried out using a Felisa oven. The samples were treated at 35°C for 19 hr, followed by 45°C for 24 hr, 65°C for 25 hr, and 30°C for 14 hr (López-Perea et al., 2008).

Malt and barley kernel analysis

The malt extract was determined using a Figueroa (1985) method. β-glucans content in the barley kernel and wort was measured with a Mixed Linkage beta--glucan (K-BGLU Megazyme International; Wicklow, Ireland). Insoluble, soluble, and total dietary fiber was determined using 32-07 of AACC method (AACC, 2000).

Statistical analysis

The results were analyzed using a 2×3 factorial experiment where the cultivars and irradiation levels were the factors. Tukey's test was also used, using the statistical package SAS 9.2 (SAS, 2008), considering a highly significant degree to $P \leq 0.05$ and 0.01, respectively.

RESULTS AND DISCUSSION

Husk and bran microstructural

The husk in malting barley usually has a range of about 7–14% of the caryopsis. There is a variation in the thickness of husk and bran layers within the same kernel. However, a significant difference in thickness was found between malting and feed barley cultivars as described below. Figure 1 shows the micrographs of husk, pericarp, and aleurone in the feed and malting barley sample of the set. The 'Esmeralda' malting barley has a pericarp thickness of ≈106 µm; the feed barleys have a higher thickness than the barley; 'Pastor Ortiz' has ≈280 µm. This data agrees with the reports that good malting barley usually has a thinner husk than feed barley (Figueroa, 1985; Rose et al., 2010). The thickness of the layers calculated from the ESEM microphotograph (Fig. 1) was similar to those reported by Delcour and Hoseney (2010).

Previously unreported measurements of outer kernel layers showed that the husk was thicker in feed barley and bran (pericarp, testa, and aleurone layer) that concentrates many β-glucans. In feed barley kernels, the husk measured 67 µm, the pericarp 72 µm, the testa 15 µm, and the aleurone layer was 124 µm, compared

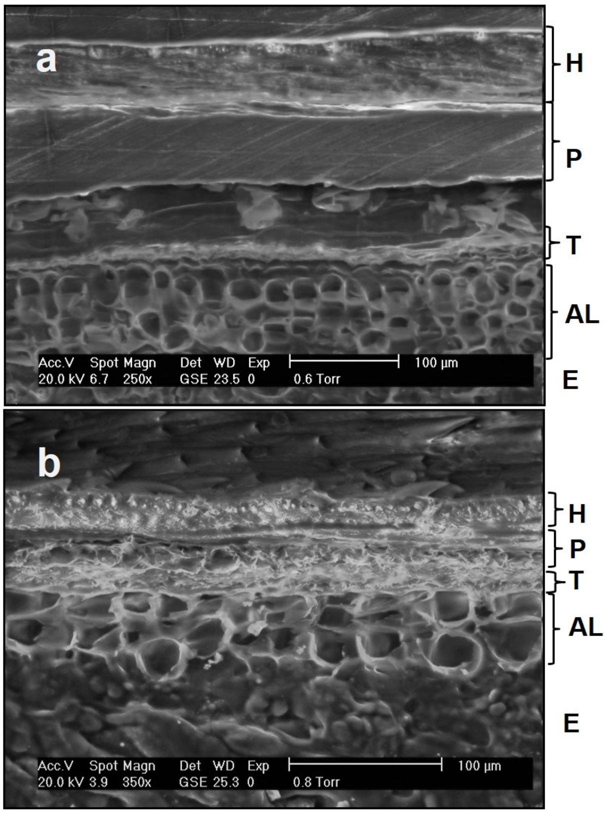

Fig. 1. Micrograph of bran layers of feed barley (**a**) and malting barley (**b**) kernel: H – husk, P – pericarp, T – testa, AL – aleurone, E – endosperm

with 23 µm, 21 µm, 14 µm, and 48 µm respectively, in malting barley. These measurements seem relevant because these tissues are essential from a nutritional point of view since the combination of phenolic acids in the wheat bran-aleurone region also has antioxidant, anticarcinogenic, and antibacterial properties (Martínez et al., 2018; Tsuda et al., 2003). The feed barley (Pastor Ortiz) had approximately double the bran thickness than 'Esmeralda'.

The results of kernel mechanical properties in the present study agree in part with previous studies. Several studies have reported a close positive relationship between the total β-glucan content and grain hardness (Henry and Cowe, 1990). This may be related to thicker endosperm cell walls in high β-glucan lines (Andersson et al., 1999). Baik and Ulrich (2008) and Pyreon et al. (2002), indicate that the degree of arabinoxylan crosslinking in cell walls may strengthen the cell walls of cereals, making harder kernels. Authors indicate that the higher proportion of β-glucans might result in thicker cell walls throughout the endosperm, rendering the barley challenging to crush (Pyreon et al., 2002; Baik and Ulrich, 2008). On the other hand, the β-glucans, pentosans, and cellulose in the husk, pericarp, and aleurone are the first barrier of the barley kernel and have different thicknesses depending on the cultivar and environmental conditions of the barley crop. Thus, the thickness of these layers could affect the viscoelastic properties, including the modulus of elasticity, and seems to be essential for selecting specific feed barley cultivars with more β-glucans and dietary fiber.

Physical and mechanical properties

The functionality of barley grain components in terms of processing is little known; more is known about barley consumption's nutritional and health benefits. The significance of grain hardness for barley malting quality has been well recognized. Allison et al. (1976), reported that malting barley varieties are usually soft, whereas non-malting varieties are usually hard. The texture of grain, more frequently referred to as hardness or softness, has a profound influence on the endosperm structure compactness and is referred to as steeliness/mealiness, which has been regarded as a valuable indicator of malting quality in barley (Darlington et al., 2000; Gamlath et al., 2008). Two cultivars were used to define the functional factors of classical malting barley. As expected, the 'Esmeralda' malting barley showed 76.1% of malt extract and 'Pastor Ortiz' 66.9% (Table 1). Malt extract is a factor of significant importance in the brewing industry. The untreated feed barleys did not reach the malting specifications established for the industry and showed low extract percentages, which implies lower industrial yield and quantity. Table 1 shows that the malting barley final stress increased to 16.4 MPa and feed barley to 31.3 MPa, but the final strain remains relatively constant in the two barley types. Some authors reported similar kernel hardness (Fox et al., 2007; Henry and Cowe, 1990; Lee et al., 1997; López-Perea et al., 2008). However, as indicated, barley hardness may also be related to different properties depending on the method used to evaluate it. In the present study, a compression test was used to evaluate the modulus

Table 1. Quality and visco-elastic properties of malting and feed barley treated with microwave

Cultivar	Type	Microwave irradiation s	Fine extract – d.b. %	Compression force N	Stress MPa	Strain %	Modulus of elasticity MPa
Esmeralda	M	0	76.1b	101.9a	16.4c	24.5ab	66.7cd
Esmeralda	M	4	83.7a	81.0b	16.9c	27.6a	61.2d
Esmeralda	M	8	74.4bc	97.9a	24.4ab	27.2a	89.4bc
Pastor Ortiz	F	0	66.9d	98.8a	31.3a	27.2a	114.1a
Pastor Ortiz	F	4	74.1bc	96.7ab	18.2bc	27.3a	66.7cd
Pastor Ortiz	F	8	72.6c	99.4a	21.6bc	23.4b	94.1ab

Means followed by the same letter in the same column are not significantly different ($P \leq 0.05$).
M – malting barley, F – feed barley, d.b. – dry basis.

of elasticity and was higher in feed barley than malting barley.

Table 1 shows the average of 10 repetitions of modulus of elasticity as measured in a single barley kernel for 'Esmeralda' malting barley, which had a value without treatment of 66.68 MPa, as compared with 114.12 MPa for 'Pastor Ortiz' without treatment. The compression force decreased from 101.0 N in malting barley and 98.83 N in feed barley, respectively. Therefore, feed barley has higher maximum stress, modulus of elasticity, and toughness than malting barley. Stasiak et al. (2007) used an acoustic method and reported the modulus of elasticity values for bulk barley 80–90 MPa for Polish barleys. In this regard, the data indicates that barley kernels' hardness and viscoelastic properties must be a suitable parameter for screening barley quality for different end-uses.

Effect of microwave heating on physical and chemical properties

Several authors reported that microwave energy produced changes in cereals' physical and chemical properties and texture (Sadeghi and Shawrang, 2008; Yanyang, et al., 2004; Walde et al., 2002). The elastic modulus in barley endosperm after microwave irradiation was characterized by very abrupt changes in the mechanical properties of the grain. Table 1 shows the microwave heating treatment from 0 to 4 s (period 1): the elastic modulus decreased in 'Esmeralda' malting barley from 66.7 MPa in control to 61.2 MPa after a treatment of 4 s. In period 2 (4 to 8 s), the elastic modulus of 'Esmeralda' kernels increased to 89.4 MPa after 8 s of microwave irradiation. The feed barley 'Pastor Ortíz' showed similar trends with 114.1 MPa in control, 66.7 MPa at 4 s, and 94.1 MPa at 8 s of microwave irradiation. López-Perea et al. (2008) reported that microwave treatment of barley kernels had an essential effect on the kernel hardness. Modulus of elasticity indicates that during heating (0–4 s), the kernel became less elastic in the first period, and the elasticity increased sharply to 30 MPa in period 2 (4–8 s). In a study with 19 malting barley, it was observed that the low β-glucan barley kernels were less elastic than the high β-glucan barley kernels and the high β-glucan barley cultivars showed higher elastic modulus than the low β-glucan barley kernel qualities (López-Perea, et al., 2012). Table 2 shows the microwave heating effect in which the β-glucan kernel content decreased at 4 s and increased at 8 s. The modulus of elasticity and hardness are correlated with the presence of β-glucans in the barley kernel. Also, Grundas et al. (2008), observed a similar effect with microwave irradiation on wheat grains using similar temperatures to this study at 20°C to 48°C but different irradiation times, 0–180 s. The hardness index (HI) decreased after 60 s but increased with a longer irradiation time.

Table 1 shows that microwave heating of kernels affected the malting performance. There was a tendency for the malt extract yield to increase in treatments from zero time to 4 s of microwave irradiation; the increase was highly significant at 7.1% for 'Pastor Ortiz' and 7.5% for 'Esmeralda'. With additional microwave

Table 2. Effect of microwave heating on non-starch polysaccharides

Cultivar	Type	Microwave irradiation s	Kernel β-glucans g/Kg	Wort β-glucans mg/L	Insoluble fiber %	Soluble fiber %	Total dietary fiber TDF %
Esmeralda	M	0	27.14c	160.99 d	24.26a	8.57b	32.83b
Esmeralda	M	4	24.84d	110.63 e	22.45c	8.98ab	31.43b
Esmeralda	M	8	26.75c	200.52 c	27.45a	9.82a	37.27a
Pastor Ortiz	F	0	34.89a	369.76 a	20.77de	2.32d	23.09d
Pastor Ortiz	F	4	27.05c	241.84 b	19.73e	3.87c	23.60d
Pastor Ortiz	F	8	31.85b	360.20 a	21.47cd	4.45c	25.92c

Means followed by the same letter in the same column are not significantly different ($P \leq 0.05$).
M – malting barley, F – feed barley.

irradiation times (8 s), the malt extract yield seemed to decrease in all barley types. From 0 to 4 s, microwave heating showed a higher difference in malt extract yield in hard feed barley compared to malting barley. The above agrees with Warchalewski et al. (2010), in that sugar content increased on wheat grains with the application of microwave heating at times of 15, 45, and 60 s, but decreased at times of 90, 120, and 180 s. It further suggests that this increase in reducing sugars is due to a higher activity of the endogenous amylase during heating at temperatures ≤48°C and decreased because the enzyme is affected by the higher temperatures. López-Perea et al. (2008) observed in barley kernels on microwave irradiation that the alpha-amylase increases at 4 s, whilst the activity decreases at 8 s. Alpha-amylase hydrolyzes starch during malting to produce reducing sugars.

Effect of microwave heating on β-glucan and dietary fiber

The total content of β-glucans in the barley kernel is given in Table 2. The content of β-glucans in barley was 24–35 g/Kg of dry mass; these results are comparable to those obtained by other Authors (Gajdošová et al., 2007; Horsley et al., 1992; López-Perea et al., 2005). The β-glucans content in the kernel was higher in feed barley, as observed in 'Pastor Ortiz' with 34.89 g/Kg and 'Esmeralda' cultivar 27.14 g/Kg. The content of β-glucans decreased due to the influence of microwave heating to 4 s, with a significant difference between control and treatment. When the time of heating was increased to 8 s, the β-glucans were low compared to the control. A similar effect was observed in the wort β-glucans content; in the cultivar, 'Pastor Ortiz' showed 369.76 mg/L of wort β-glucans and 'Esmeralda' with 160.99 mg/L (Table 2). The β-glucans in the barley kernel were affected by microwave heating, and this effect is reflected in the wort β-glucans content. Microwave heating for 4 s was enough to decrease the β-glucans in the wort for malting barley and feed barley, which were significantly different from the control. The 'Esmeralda' cultivar showed high extractability of β-glucans after 8 s of microwave heating (200.52 mg/L) – more than control. In the case of 'Pastor Ortiz', the extractability of β-glucans was the same after 8 s as the control and was not significantly different. These data agree with previous reports showing increases in β-glucan's extractability after thermal processing (Knuckles et al., 1997; Temelli, 1997; Yiu et al., 1991). The reduction of β-glucan content due to microwave heating is an essential contribution to the brewing industry. The β-glucans have been recognized as a potential cause of problems in the brewing process. This includes poor conversion during the mashing, difficulty lautering wort and beer filtration, and producing the final product's colloidal turbidity (Bamforth, 1982). The high content of β-glucans characterizes feed barley, so they are not used to produce beer; with microwave treatments to 4 s.

On the other hand, the β-glucans content was correlated with mechanical properties, the hardness expressed as compression force had a high correlation with the β-glucans $r = 0.87$, and the correlation with the modulo of elasticity was $r = 0.92$. Similar results were obtained by Nielsen (2003) and Gamlath et al. (2008). These authors reported that the hardness had a high correlation with β-glucans $r = 0.86$.

Zia-Ur and Shah (2005) found that cooking processing affected the cellulose and hemicelluloses of different food legumes. Barley heated with microwaves affected insoluble, soluble, and dietary fiber (Table 2). The insoluble fiber was affected after 4 s of microwave irradiation, with a lower value than the control. However, increasing the irradiation time increased the insoluble fiber for 'Esmeralda' and 'Pastor Ortiz'. Svanberg et al. (1997) observed green beans treated with microwave heating and the arabinose, xylose, and uronic acids content as part of insoluble fiber. There was a decrease in molecular weight, resulting in less insoluble fiber. It is also possible to generate breaks in the weak bonds of the cell wall polysaccharides or between polysaccharides-protein, increasing the insoluble fiber (Marconi et al., 2000). The soluble fiber showed the opposite behavior. The soluble fiber increased in the two cultivars with a higher heating time of 8 s, compared to the control. The total dietary fiber (TDF) had the same trend as the insoluble fiber, the TDF increasing with a temperature higher than 30°C or time of microwave heating. When the barley is irradiated, these changes in the fiber content must be possible for the microwaves to affect the β-glucan chains and reduce the size of this polysaccharide. Therefore, with heating, the β-glucans have more extractability, and the soluble fiber increases. Knuckles et al. (1997) reported that the β-glucan molecular weight decreased as the water temperature of extraction increased from 25, 65°C to 100°C. Rose et al. (2010), indicated that food processing conditions might affect the extractability and molecular weight of β-glucans and arabinoxylans in cereal products.

CONCLUSIONS

The mechanical properties of barley kernels may be evaluated with the compression loading method and could be a proper parameter for the screening of barley quality for different end-uses, from malt to beer produce, flour to baking products, or other food products. The thickness of the bran influenced the mechanical properties of the grain. Also, microwave irradiation affects the mechanical, malting quality, β-glucans, and total dietary fiber content of barley kernels. The best irradiation time for malting quality was 4 s because it increased the malt extract yield. Microwave heating may affect β-glucan chains and fiber constituents.

ACKNOWLEDGMENTS

We wish to acknowledge Jose Juan Veles Medina and Jose Eleazar Urbina Alvarez from the Department of Material Science, area of Bio-Organic Materials at the CINVESTAV Mexico, for their technical assistance.

REFERENCES

AACC (2000). International approved methods of analysis, 10th ed. Methods 32-07. St. Paul, MN: AACC International.

Allison, M. J., Cowe, I. A., McHale, R. (1976). A rapid test for the prediction of malt quality. J. Inst. Brew. 82, 166–167. https://doi.org/10.1002/j.2050-0416.1976.tb03743.x

Andersson, A. A. M., Elfverson, C., Andersson, R., Regner, S., Aman, P. (1999). Chemical and physical characteristics of different barley samples. J. Sci. Food Agric., 79, 979–986. https://doi.org/10.1002/(SICI)1097-0010(19990515)79:7%3C979::AID-JSFA313%3E3.0.CO;2-L

Baik, B. K., Ulrich, S. E. (2008). Barley for food: Characteristics, improvement, and renewed interest. J. Cereal Sci., 48, 233–242. https://doi.org/10.1016/j.jcs.2008.02.002

Bamforth, C. W. (1982). Barley β-glucans, their role in malting and brewing. Brew. Digest., 22, 5–6.

Darlington, H. F., Tesci, L., Harris, N., Griggs, D. L., Cantrell, I. C., Shewry, P. R. (2000). Starch granule associated proteins in barley and wheat. J. Cereal Sci., 32, 21–29. https://doi.org/10.1006/jcrs.2000.0312

Delcour, J. A., Hoseney, R. C. (2010). Principles of cereal science and technology, 3rd ed. St. Paul, MN: AACC International.

Dolinska, R., Warchalewski, J. R., Gralik, J., Jankowski, T. (2004). Effect of g-radiation and microwave heating of wheat grain on some starch properties in irradiated grain as well as in grain of the next generation crops. Nahrung/Food, 48(3), 195–200. https://doi.org/10.1002/food.200300380

Figueroa, J. D. C., Hernández, Z. J. E., Véles, M. J. J., Rayas-Duarte, P., Martínez-Flores, H. E., Ponce-García, N.

(2011). Evaluation of the degree of elasticity and other mechanical properties of wheat kernels. Cereal Chem., 88, 12–18.

Figueroa, J. D. C. (1985). Métodos para evaluar la calidad maltera de la cebada (pp. 115–120). Tema Didáctico 17. México: SARH-INIA.

Fox, G. P., Osborne, B., Bowman, J., Kelly, A., Cakir, M., Poulsen, D., ..., Henry, R. (2007). Measurement of genetic and environmental variation in barley (*Hordeum vulgare*) grain harness. J. Cereal Sci., 46, 82–92. http://dx.doi.org/10.1016/j.jcs.2006.12.003

Gajdošová, A., Petruláková, Z., Havrlentoná, M., Červená, V., Hozoná, B., Šturdík, E., Kogan, G. (2007). The content of water-soluble and water-insoluble β-D-glucans in selected oats and barley varieties. Carbohydr. Polym., 70, 46–52. https://doi.org/10.1016/j.carbpol.2007.03.001

Gamlath, J., Aldred, G. P., Panozzo, J. F. (2008). Barley (1→3: 1→4) β-glucans and arabinoxylan content are related to kernel hardness and water uptake. J. Cereal Sci., 47, 365–371. https://doi.org/10.1016/j.jcs.2007.05.017

Grundas. S., Warchalewski, J. R., Dolinska, R., Gralik, J. (2008). Influence of microwave heating on some physicochemical properties of wheat grain harvested in three consecutive years. J. Cereal Chem., 85(2), 224–229.

Henry, R. J., Cowe, I. (1990). Factors influencing the hardness (milling energy) and malting quality of barley. J. Inst. Brew., 96, 135–136. https://doi.org/10.1002/j.2050-0416.1990.tb01024.x

Horsley, R. D., Schwarz, P. B., Faue, A. C., Manthey, F. A. (1992). Survey of β-glucan content of barley cultivars adapted to North Dakota. North Dakota Farm Res., 49(5), 4–26.

Khraisheh, M. A. M., McMinn, W. A. M., Magee, T. R. A. (2004). Quality and structural changes in starchy foods during microwave and convective drying. Food Res. Intern., 37, 497–503. https://doi.org/10.1016/j.foodres.2003.11.010

Knuckles, B. E., Yokoyama, W. H., Chiu, M. M. (1997). Molecular characterization of barley beta-glucans by size-exclusion chromatography with multiple-angle laser light scattering and other detectors. J. Cereal Chem., 74(5), 599–604.

Lee, C. J., Horsley, D., Manthey, F. A., Schwarz, P. B. (1997). Comparation of β-glucan content of barley and oat. J. Cereal Chem., 74 (5), 571–575.

López-Perea, P., Schwarz, P. B., Figueroa, J. D. C., Hernández-Estrada, Z. J. (2012). Effect of β-glucans on viscoelastic properties of barley kernels and their relationship to structure and soluble dietary fibre. J. Cereal Sci., 56(3), 595–602. https://doi.org/10.1016/j.jcs.2012.07.017

López-Perea, P., Figueroa, J. D. C., Rodríguez-Chong, A., Hernández-Estrada, Z. J. (2011). Effect of microwave irradiation on the elastic properties of cereal kernels and its relation to quality In R. N. Chibbar, J. E. Dexter (Eds.), Wheat science dynamics: Challenges and opportunities (pp. 363–370). India: Agrobios.

López-Perea, P., Figueroa, J. D. C., Sevilla, P. E., Román, G. A., Reynoso, R., Martínez, P. R. (2008). Changes in barley kernel hardness and malting quality by microwave irradiation. J. Am. Soc. Brew. Chem., 66(4), 203–207. https://doi.org/10.1094/ASBCJ-2008-0811-01

López-Perea, P., Guzmán, F. A. O., Santos, E. M. L., Prieto, F. G., Román, A. D. G. (2005). Evaluación de la calidad física de diferentes variedades (*Hordeum sativum* jess) cultivadas en los estados de Hidalgo y Tlaxcala, México. Rev. Chil. Nut., 32, 247–253. http://dx.doi.org/10.4067/S0717-75182005000300010

Marconi, E., Rugger, S., Cappelloni, M., Leonardi, D., Carnovale, E. (2000). Physicochemical, nutritional, and microstructural characteristics of chickpeas (*Cicer arietinum* L.) and common beans (*Phaseolus vulgaris* L.) following microwave cooking. J. Agric. Food Chem., 48, 5986–5994. https://doi.org/10.1021/jf0008083

Martínez, M., Motilva, M. J., López de las Hazas, M. C., Romero, M., Vaculova, K., Ludwig, I. A. (2018). Phytochemical composition and β-glucan content of barley genotypes from two different geographic origins for human health food production. Food Chem., 245, 61–70. https://doi.org/10.1016/j.foodchem.2017.09.026

Nielsen, J. P. (2003). Evaluation of malting barley quality using exploratory data analysis II. The use of kernel hardness and image analysis as screening methods. J. Cereal Sci., 38, 247–255. https://doi.org/10.1016/S0733-5210(03)00024-9

NMX-FF-043-SCFI-2003. Productos alimenticios no industrializados para consumo humano-cereal-cebada maltera (*Hordeum vulgare* L. y *Hordeum distichum* L.). Especificaciones y métodos de prueba. Publicada en el diario oficial el 18 de octubre, 2003.

Pino, J. L., Mujica, V., Arredondo, M. (2021). Effect of dietary supplementation with oat β-glucan for 3 months in subjects with type 2 diabetes: A randomized, double-blind, controlled clinical trial. J. Funct. Foods, 77, 104311. https://doi.org/10.1016/j.jff.2020.104311

Ponce-García, N., Figueroa, J. D. C., López-Huape, G. A., Martínez, H. E. Martínez-Peniche, R. (2008). Study of visco-elastic properties of wheat kernels using the compression load method. J. Cereal Chem., 85(5), 667–672. https://doi.org/10.1094/CCHEM-85-5-0667

Pyreon, S., Mabille, F., Devaux, M. F., Autran, J. C. (2002). Influence of structural characteristics of aleurone layer on milling behavior of durum wheat (*Triticum durum* Desf.). J. Cereal Chem., 80(1), 62–67. http://dx.doi.org/10.1094/CCHEM.2003.80.1.62

Rose, D. J., Sanghoon, K., Inglett, G. E. (2010). Influence of jet-cooking and pH on extraction and molecular weight of beta-glucans and arabinoxilan from barley (*Hordeum vulgare* Prowashonupana). J. Cereal Chem., 87(6), 607–611. https://doi.org/10.1094/CCHEM-04-10-0059

Roudi, R., Mohammadi, S. R., Roudbary, M., Mohsenzadegan, M. (2017). Lung cancer and β-glucans: review of potential therapeutic applications. Invest. New Drugs, 35, 509–517. https://doi.org/10.1007/s10637-017-0449-9

Sadeghi, A. A., Shawrang, P. (2008). Effects of microwave irradiation on ruminal dry matter, protein and starch degradation characteristics of barley grain. Anim. Feed Sci. Tech., 141, 184–194. https://doi.org/10.1016/j.anifeedsci.2007.05.034

SAS (2008). User's guide, version 8. Cary, NC: SAS Institute.

Stasiak, M., Molienda, M., Harabik, J. (2007). Determination of modulus of elasticity of cereals and rapeseeds using acoustic method. J. Food Eng., 82, 51–57. https://doi.org/10.1016/j.jfoodeng.2007.01.017

Schlörmann, W., Glei, M. (2017). Potential health benefits of β-glucan from barley and oat. Ernahrun. Umsch., 64(10), 145–149. https://doi.org/10.4455/eu.2017.039

Svanberg, S. J. M., Suortti, T., Nyman, E. M. G. L. (1997). Physicochemical changes in dietary fiber of green beans after repeated microwave treatments. J. Food Sci., 62(5), 1006–1010. https://doi.org/10.1111/j.1365-2621.1997.tb15025.x

Temelli, F. (1997). Extraction and functional properties of barley beta-glucan as affected by temperature and pH. J. Food Sci., 62(6), 1194–1198. https://doi.org/10.1111/j.1365-2621.1997.tb12242.x

Tsuda, T., Horio, F., Uchida, K., Aoki, H., Osawa, T. (2003). Dietary cyanidin-3-orto-beta-D-glucoside-rich purple corn color prevents obesity and ameliorates hyperglycemia in mice. J. Nutr., 133, 2125–2130. https://doi.org/10.1093/jn/133.7.2125

Vadivanbal, R., Jayas, D. S. (2007). Changes in quality of microwave-treated agricultural products – a review. Biosyst. Eng., 98, 1–16. https://doi.org/10.1016/j.biosystemseng.2007.06.006

Walde, S. G., Balaswamy, K., Velu, V., Rao, D. G. (2002). Microwave drying and grinding characteristics of wheat (*Triticum aestivum*). J. Food Eng., 55(3), 271–276. https://doi.org/10.1016/S0260-8774(02)00101-2

Warchalewski, J. R., Gralik, J. (2010). Influence of microwave heating on biological activities and electrophoretic pattern of albumin fraction of wheat grain. Cereal Chem., 87(1), 35–41. https://doi.org/10.1094/CCHEM-87-1-0035

Warchalewski, J. R., Gralik, J., Wojtasiak, R. Z., Zabielski, J., Kuśnierz, R. (1998). The evaluation of wheat grain odour and colour after gamma and microwave irradiation. EJPAU, 1(1), #04. Retrieved from http://www.ejpau.media.pl/volume1/issue1/food/art-04.html.

Yanyang, X., Min, Z., Mujumdar, A. S., Le-qun, Z., Jin-cai, S. (2004). Studies on hot air and microwave vacuum drying of wild cabbage. Drying Tech., 22(9), 2201–2209. https://doi.org/10.1081/DRT-200034275

Yiu, S. H., Weisz, J., Word, P. J. (1991). Comparison of the effects of microwave and conventional cooking on starch and beta-glucans in rolled oats. J. Cereal Chem., 68, 372–375.

Zia-Ur, R., Shah, W. H. (2005). Thermal heat processing effects on antinutrients, protein and starch digestibility of food legumes. Food Chem., 91, 327–331. https://doi.org/10.1016/j.foodchem.2004.06.019