Some physical and mechanical properties of roasted Zerun wheat

Nursel Develi Işıklı · Belma Şenol · Nafi Çoksöyler

Revised: 23 December 2011 / Accepted: 9 April 2012 / Published online: 27 April 2012
© Association of Food Scientists & Technologists (India) 2012

Abstract Some physical and mechanical properties of roasted Zerun wheat were investigated in the moisture range from 8.80 % to 23.40 % wet basis. Mechanical properties were evaluated by examining the effect of moisture content upon the grain rupture force, energy and Weibull parameters. Length, width, thickness, porosity and angle of repose increased nonlinearly from 6.09 to 6.36 mm; 4.17 to 4.18 mm; 2.66 to 2.78 mm; 37.71 % to 39.09 % and 33.02° to 37.90°, respectively when moisture content increased. The Weibull distribution fits the data for rupture force and energy. The Weibull modulus and scale parameter for rupture force varied between 3.88 and 6.20; 26.61 and 44.24N, respectively. The Weibull modulus for energy increased from 2.15 to 3.24 with increased in moisture content. Measured mechanical properties of grains showed that the brittleness and fragile structure of the roasted grain gradually lost its characteristic crispiness and become soft and ductile above 13.78 % moisture content.

Keywords Roasted Zerun wheat · Physical properties · Moisture content · Rupture force · Weibull analysis

Introduction

Roasted wheat made from whole grains is used as a snack food in central Anatolia region of Turkey and it is known as “kavurga”. Roasted wheat ‘kavurga’ is produced from bread wheat preferably, zerun wheat. Zerun wheat varieties suitable for conditions in central Anatolia are located in the groups of white hard wheat and they are susceptible to plant diseases and resistant to drought and winter. Steel pan heated by wood fire is used for the production of roasted wheat “kavurga”. After warming up the pan, sieved wheat is placed on the pan and the wheat grains are continuously stirred to avoid burning of grains and to achieve a homogeneous roasting process. In this process, the manufacturers exposed to the influence of smoke and flame. Roasted zerun wheat is usually consumed as grain. However depending on consumer preferences, roasted wheat can be milled and mixed with syrup or molasses before consumption. Roasted zerun wheat is generally produced in homes for domestic consumption or commercially produced by small-scale manufacturers. Furthermore, roasted zerun wheat remains as one of the traditional foods consumed in special days specific to that region.

Recent research has shown that whole-grain food consumption is associated with reduced risks of various types of chronic diseases such as cardiovascular disease (Jensen et al. 2004; Katcher et al. 2008; Tighe et al. 2010), risk of hypertension (Wang et al. 2007), inflammatory mortality (Jacobs et al. 2007), diabetes and weight gain (Koh-Banerjee et al. 2004). Whole grains are rich sources of fibre, vitamins, minerals and phytochemicals including phenolics, carotenoids, vitamin E, lignans, β -glucan, inulin, resistant starch, sterols and phytates (Liu 2007). Protective effects of whole grains are attributed to these nutrients contained in them. A whole-grain food includes all edible parts of the grain: the bran, the germ and the endosperm and most of the healthy

N. D. Işıklı (✉)
Department of Food Engineering, Faculty of Engineering,
University of Cumhuriyet,
Sivas, Turkey
e-mail: nisikli@yahoo.com

B. Şenol
Department of Food Technology, Zara Ahmet Çuhadaroğlu
Vocational School, University of Cumhuriyet,
Zara, Sivas, Turkey

N. Çoksöyler
Department of Food Engineering, Faculty of Agriculture,
University of Yüzüncü Yıl,
Van, Turkey

components of grain are situated in the bran and germ. In refined-grain products, the endosperm is separated from the bran and germ; therefore, most of the grains nutritional value is lost during the refining process (Jacobs and Steffen 2003). Roasting enhances the flavor and improved sensory properties of the grains. High temperatures used during roasting process generate superheated steam and build pressure within the grain. Majority of grains get popped during roasting process due to high internal pressure that is a function of moisture content and temperature of grain and roasting time (Jha 2005). Popping of wheat grains is also desirable during the manufacturing of roasted zerun wheat. For this reason, moisture content of wheat grain is important. Tempering which is generally applied to create a small gap between shell and grain, gelatinizes the starch of the grain and equilibrate the moisture in popping process (Jha 2005). However, tempering process is not applied in manufacture of roasted zerun wheat at central Anatolia region of Turkey.

Brittleness of the roasted zerun wheat is the most important characteristic in terms of consumer preferences. The puffed cereals have a highly hygroscopic matrix because of the new organization of the outer layers and the high porosity (Mariotti et al. 2006). They rapidly take up moisture when exposed to certain atmospheric environments during storage. It is known that water is the most effective plasticizer in food matrices. Increased water content in dry food causes swelling of the solid matrix and lowers glass transition temperature (T_g) and mechanical resistance (Fennema 1996). The effect of water plasticization on the textural properties of a solid system could be determined by mechanical evaluation. In addition, Weibull analysis can be used to describe the fracture behavior of the heterogeneous and glassy material (Aarseth and Prestløkken 2003; Łysiak 2007). In some processed products like cereal extrudates and snacks, the level of water content is the main determinant for their characteristic brittleness, crispness or crunchiness. Increasing the moisture content of these products during storage could affect the starch/protein matrix, altering the strength and lowering the sensorial acceptability of the product (Pamies, et al. 2000; Pittia and Sacchetti 2008).

Knowledge about the physical properties of processed and raw materials is extremely important to the selection of optimal processing parameters and conditions. All physical properties such as shape and dimensions, volume, weight, sorption properties and porosity are subjected to various changes as a result of technological requirements. Even during the simplest technological operations, all physical properties are affected by changes in moisture content of the seed and the storage conditions (Panasiewicz et al. 2009). The physical properties of various seeds and fruits as a function of moisture content were studied such as caper seed by Dursun and Dursun (2005), pomegranate seeds by Kingsly et al. (2006), coriander seeds by Coşkuner and

Karababa (2007), cornelian cherry by Nalbandi et al. (2009), chickpea seed by Nikoobin et al. (2009), jatropha fruit by Pradhan et al. (2009), locust bean seed by Sobukola and Onwuka (2010), wheat kernel by Babić et al. (2011), lathyrus grain by Kenghe et al. (2011) and paddy rice by Adebawale et al. (2011).

The physical properties of roasted wheat, like those of other grains, are important for the design of equipment for processing, separating, packing and transportation. Moreover, knowledge of the mechanical properties is a key parameter for the evaluation of textural characteristics of the roasted wheat.

In this study, some of the moisture dependent physical and mechanical properties of roasted zerun wheat were investigated at four levels of moisture content ranging from 8.80 % to 23.40 % wet basis (w.b). Those properties investigated were: linear dimensions, geometric mean diameter, mass of 1,000 roasted grain, true density, bulk density, porosity, angle of repose, rupture force and energy. Additionally, the relationship between the Weibull parameters and the mechanical properties such as rupture force and rupture energy were examined.

Materials and methods

Zerun wheat was obtained from a wheat market in Sivas province of Turkey. The raw grains were cleaned manually to remove all foreign material and broken grains. Then the raw grains were roasted in a steel pan heated by wood fire. In this process, the raw grains were continuously stirred to avoid burning of grains and to achieve a homogeneous roasting. Initial moisture content of raw and roasted wheat was determined by drying it in an oven at 103 °C (Al-Mahasneh and Rababah 2007). Initial moisture of the raw and roasted wheat was 12.50 % and 8.80 %, respectively.

Roasted grains were moistened to the desired moisture content by adding necessary amount of distilled water as calculated from the following relation

$$Q = W_i \times (M_f - M_i) \quad (1)$$

Where Q is the mass of water added in kg; W_i is the initial mass of the sample in kg dry basis (d.b); M_i is the initial moisture content of the sample in % d.b. and M_f is the final moisture content of the sample in % d.b.

Roasted samples at the desired moisture contents were placed in separate polythene bags and the bags were sealed tightly. All the bags were stored in a refrigerator at 5 °C for 1 week to allow a uniform distribution of moisture throughout the sample. Before each test, the required quantity of sample was taken out of the refrigerator and allowed to warm up to room temperature and before the moisture content was determined.

All physical and mechanical properties of roasted grain were determined at the moisture content of 8.80, 13.78, 18.55 and 23.40 % w.b. The relationships between all physical properties and moisture content of roasted grain were evaluated by analysis of regression using SPSS software package for Windows version 11.0 (2008 SPSS Inc.).

To determine the dimensions of the roasted grain, hundred grains were randomly selected at the desired moisture content. Then length (L), width (W) and thickness (T) of the grains were measured using a micrometer with an accuracy of ± 0.01 mm.

The geometric mean diameter, D_g , and sphericity, Φ , of the selected grains were calculated by using the following relationships (Mohsenin 1980),

$$D_g = (LWT)^{1/3} \quad (2)$$

$$\phi = \frac{(LWT)^{1/3}}{L} \quad (3)$$

where L is length, W is width and T is thickness, all in mm

The mass of 1,000-roasted Zerun wheat was determined by counting 100 roasted grain at the desired moisture content, weighing them on a digital electronic balance and then multiplying the result by 10 to give the mass of 1,000-roasted Zerun wheat.

True density (q_t) of raw and roasted wheat as a function of moisture content was determined by using the liquid displacement method. Toluene was used instead of water in order to avoid absorption of water during the experiment. Fifty milliliter of toluene was placed in a 100 ml graduated measuring cylinder and 5 g sample was immersed in toluene. The amount of displaced toluene was recorded from the graduated scale of the cylinder. The true density (kg m^{-3}) was found as the ratio of mass of sample to the volume of displaced toluene (Coşkun and Karababa 2007; Nikoobin et al. 2009).

To determine the bulk density (q_b), a 100 ml cylindrical glass container was filled completely with roasted grain. The container was tapped several times and the excess grains were removed without compressing the grains. Then, its content was weighed by an electronic balance. Bulk density (kg m^{-3}) was calculated by taking the ratio of mass of roasted grain to their bulk volume (Coşkun and Karababa 2007; Kahyaoğlu et al. 2010; Karaj and Müller 2010).

The porosity of roasted wheat at various moisture contents was calculated from its bulk (q_b), and true (q_t) densities using the relationship given by Mohsenin (1980) as follows.

$$\varepsilon = \frac{q_t - q_b}{q_t} \times 100 \quad (4)$$

where q_b and q_t are the bulk density and the true density, respectively.

A glass box $15 \times 15 \times 3 \text{ cm}^3$ with a removable side panel was used to determine the angle of repose. The box was filled with the roasted wheat at the moisture content being investigated, and the side panel was quickly removed allowing the roasted grain to flow to their natural slope. The angle of repose was determined from measurements of height of roasted wheat, H, and the horizontal width, X. The angle of repose (θ) was calculated by using the following relationships

$$\theta = \tan^{-1} \left[\frac{H}{X} \right] \quad (5)$$

Mechanical properties such as rupture force and energy of roasted grain were also assessed at the moisture content levels being investigated. A universal testing machine (Hounsfield H5K-S) equipped with a 1 kN load cell was used for determining rupture force along the length of the roasted grains. Roasted grains were loaded between two flat parallel plates in this device and compressed at a crosshead speed of 2 mm/min until rupture occurred. The rupture point was detected by a sudden decrease in resisting force due to grains that were broken or cracked at that point. As soon as the rupture point was detected, the compression was stopped and the rupture force (N) and deformation (mm) were recorded. For each moisture content level, 20 grain were randomly selected and tested using the above setup. The rupture energy was determined by calculating the area under force deformation curve from the following equation (Altuntaş and Yıldız 2007; Singh et al. 2010):

$$Er = \left[\frac{Fr \times Dr}{2} \right] \quad (6)$$

where Fr is the rupture force and Dr is the deformation at rupture point

Weibull statistic was applied to describe rupture force and energy levels. The cumulative distribution function that gives the probability of fracture $F(x)$ at a rupture force or energy level x is expressed as (Aarseth and Prestlökken 2003; Łysiak 2007).

$$F(x) = 1 - \exp \left[- \left(\frac{x}{x_0} \right)^m \right] \quad (7)$$

Where m is the Weibull modulus and x_0 is the scale parameter. This function corresponds to the exponential function for $m=1$ and has a sigmoidal shape for $m>1$. The scale parameter x_0 is the rupture force or energy level that causes failure in 63.2 % of cases.

In probability plotting, the Weibull parameters are estimated by reformulating Eq. (7) according to Aarseth and Prestlökken (2003) and Łysiak (2007). Reformulating Eq. (7) yields

$$\ln \left[\ln \left(\frac{1}{1 - F(x)} \right) \right] = m \ln x - m \ln x_0 \quad (8)$$

Weibull modulus (m) and scale parameter (x_0) can be estimated by plotting $\ln [\ln(1/1-F(x))]$ against the $\ln x$, and using linear regression. The slope of the regression line is m , and intercept is equal to $m \ln x_0$ in the Weibull plot. Scale parameter (x_0) is estimated from the intercept ($m \ln x_0$).

For estimating $F(x)$; rupture force or energy values were ranked from smallest to highest and assigned a number i between 1 and n for each observation, where n is the number of specimens tested. The probability for i 'th grain was calculated from

$$F(x) = \frac{(i - 0.5)}{n} \quad (9)$$

The force or energy that is required for fracturing 99 % of the grains, $x_{0.99}$, was estimated using the relationship given by Aarseth and Prestlökken (2003) as follows

$$x_{0.99} = x_0 \left[\ln \left(\frac{1}{1 - F(x)} \right) \right]^{\frac{1}{m}} \quad (10)$$

Where, $F(x)$ is equal to 0.99.

Results and discussion

Size and shape

The moisture dependence of roasted grain axial dimensions for the moisture content ranging from 8.80 to 23.40 % w.b. is shown in Fig. 1. Roasted wheat samples of 13.78, 18.55 and 23.40 % moisture content were prepared by adding water to the randomly separated portions of the bulk having a moisture content of 8 %. As moisture content increased from 8.80 % to 23.40 % (w.b.); roasted grain length increased from 6.09 to 6.37 mm (4.44 % increase), roasted grain thickness increased from 2.65 to 2.76 mm (4.15 % increase) and roasted grain width increased from 4.17 to 4.18 mm. This indicates that, the capillaries and voids in roasted grain filled with water and then the roasted grain swelled and its axial dimensions increased. This increases in length and thickness of roasted grains were found statistically significant ($p < 0.01$). Similar results have been reported for soybean (Dehspande et al. 1993) and popcorn kernel (Karababa 2006). The dimensions of roasted grain had the following relationship with moisture content

$$\begin{aligned} L &= -0.0006 M^2 + 0.0383 M + 5.7802; R^2 = 0.941 \\ W &= -0.0001 M^2 + 0.004 M + 4.1435; R^2 = 0.938 \\ T &= -0.0006 M^2 + 0.0287 M + 2.4519; R^2 = 0.999 \end{aligned}$$

The variation of the geometric mean diameter of the roasted grains is displayed in Fig. 1. The geometric mean diameter (Dg) increased non-linearly with grain moisture content. The relationships between the geometric mean

diameter and grain moisture content was significant ($p < 0.01$) and the variation in geometric mean diameter, can be expressed by the following equation

$$Dg = -0.0005 M^2 + 0.0228 M + 3.9063; R^2 = 0.999$$

The geometric-mean diameter of the roasted grain was found to be more than that of its thickness. Similar results reported for green wheat (Al-Mahasneh and Rababah 2007), wheat (Nalbandi et al. 2010) and guar seeds (Vishwakarma et al. 2011).

As shown in Fig. 1 the sphericity of the roasted grain decreased nonlinearly with increase in moisture content ($p > 0.05$). The relationship between sphericity (ϕ) and moisture content is expressed as

$$\phi = -0.00003 M^2 + 0.0003 M + 0.6671; R^2 = 0.990$$

This decrease could be attributed to the more expansion of roasted grain length than that of its width. The decreased in sphericity upon addition of moisture have been reported for bambara groundnut (Baryeh 2001) and guar seed (Vishwakarma et al. 2011).

Thousand roasted grain mass

The mass of 1,000 roasted grain (M_{1000}) in g increased linearly from 3.10 to 4.89 g as the moisture content, M , increased from 8.80 % to 23.40 % w.b. (Fig. 1). This relationship was significant ($p < 0.01$) and the linear equation for 1000 roasted grains mass can be formulated as

$$M_{1000} = 0.5253 M + 32.795; R^2 = 0.992$$

A similar trend was reported for other seeds and fruits (Balasubramanian and Viswanathan 2010; Işıklı and Yılmaz 2011)

True and bulk density

The variation of true density (q_t) and bulk density (q_b) with roasted grain moisture content is shown in Fig. 1. As the grain moisture content increases from 8.80 % to 23.40 %, the true and bulk density increase linearly from 774 to 871 kg m⁻³ and from 482 kg m⁻³ to 530 kg m⁻³, respectively. The variation in bulk density and true density with moisture content was significant ($p < 0.001$) and these relationships may be expressed as:

$$\begin{aligned} q_t &= 6.6816 M + 715.21; R^2 = 0.999 \\ q_b &= 3.3179 M + 454.62; R^2 = 0.989 \end{aligned}$$

The measured values of bulk and true density were smaller when compared with the reported results of El-Khayat et al. (2006) for Syrian hard wheat and Babić et al. (2011) for the Simonida and Dragana varieties (hard wheat).

Fig. 1 Effect of moisture content on physical characteristics of roasted Zerun wheat ($n=100$ for axial dimensions, geometric-mean diameter and sphericity; $n=3$ other physical properties at each moisture level)

Increase in the moisture content between 8.80 % and 23.40 % leads to increase both the mass and volume of roasted grain. Roasted grain volume increased by

8.30 %, and mass of 1,000 grains increased by 19.95 % with increasing moisture content. Therefore the increase in true and bulk density was mainly due

Table 1 Observed median values for rupture force and Weibull parameters

Moisture content, %	Rupture force ^a , N	Weibull parameters			K-S test ^b	Force for 99 % grain breaking
		Weibull modulus, m_f	Scale parameter, x_{f0}	Coefficient of determination, R^2		
8.80	32.2	3.9	35.6	0.921	0.11	52.8
13.78	39.5	5.2	44.7	0.975	0.11	59.9
18.55	35.5	6.2	38.9	0.899	0.15	49.8
23.40	24.1	5.2	26.9	0.888	0.17	36.1

^a Observed median values for rupture force; $n=20$

^b Kolmogorov-Smirnov test

Table 2 Observed median values for rupture energy and Weibull parameters

Moisture content, %	Rupture energy ^a , J	Weibull parameters			K-S test ^b	Energy for 99 % grain breaking
		Weibull modulus, m_e	Scale parameter, x_{e0}	Coefficient of determination, R^2		
8.80	8.2	2.2	10.3	0.925	0.11	21.0
13.78	16.5	2.2	16.9	0.952	0.13	33.7
18.55	16.9	2.7	20.4	0.942	0.13	36.2
23.40	17.6	3.2	20.7	0.940	0.15	33.1

^a Observed median values for rupture energy; $n=20$ ^b Kolmogorov-Smirnov test

to the higher levels of increase in the mass of the grain compared to the increase in volume of the grain. This was similar to the results obtained by Aydın and Özcan (2002) for terebinth fruits and by Kingsly et al. (2006) for pomegranate seeds. Baryeh and Mangope (2002) found both true density and bulk density of pigeon peas to increase nonlinearly with increase in seed moisture content. A linear increase of true density with increasing the moisture content has been observed by Baryeh (2002) for millet, Vilche et al. (2003) for quinoa seeds and Altuntaş and Yıldız (2007) for faba bean grain.

Porosity

As shown in Fig. 1 porosity (ϵ) of roasted grains increased nonlinearly as the moisture content increased ($p<0.001$). The variation of porosity with moisture content can be expressed as

$$\epsilon = 0.0073 M^2 - 0.1388M + 38.347; R^2 = 0.989$$

The increase in porosity over 13.78 % moisture could be explained by the higher expansion in length of roasted grain

in comparison to its width and hence, the decrease in its sphericity.

The angle of repose

The angle of repose of roasted grain (θ) was observed to increase from 33.02 to 37.90 (Fig. 1). The angle of repose is a characteristic of bulk material which is an indication of the cohesion among the individual grains. The surface layer moisture surrounding the individual grains holds the aggregate of grains together by the surface tension (Pradhan et al. 2009). As the moisture contents of grain increase from 8.80% to 23.40 %, it will increase the cohesion among the individual grains, which in turn will also increase the angle of repose. The variation in angle of repose of roasted grain follows a second-order polynomial relationship with moisture content ($p<0.01$) which is represented by:

$$\theta = 0.0178M^2 - 0.2539M + 33.993; R^2 = 0.979$$

Similar results were obtained for bambara groundnuts, cocoa beans, coriander seeds and barnyard millet grains and

Fig. 2 Weibull probability plots for rupture force of roasted grains at different moisture content

kernels (Baryeh 2001; Bart-Plange and Baryeh 2003; Coşkuner and Karababa 2007; Singh et al. 2010).

Rupture force

The experimental results for rupture force and absorbed energy along the length at different moisture content are presented in Tables 1 and 2. For each moisture content, Weibull probability plots fit to linear relations with high determination coefficients ranging from 0.888 to 0.975 for rupture force and from 0.9253 to 0.9516 for energy levels (Tables 1 and 2 and Fig. 2). The Kolmogorov-Smirnov test (K–S test) shows that the force and energy at rupture point could be adequately represented with the Weibull parameters for all moisture contents (the critical value at significance level 0.05 is 0.27 for 8.80 %, 13.78 % and 18.55 % moisture content and 0.36 for 23.40 % moisture content), (Tables 1 and 2). Crispness is important to consumer acceptance of low moisture cereal-based snack foods. Therefore, the estimated force or energy levels that are required for fracturing in 99 % of the grains, $x_{0.99}$, are calculated in Eq. (10) and are given in Tables 1 and 2. The observed median value of rupture force, scale parameter, x_{f0} , and estimated force, $x_{f0.99}$, of roasted Zerun grain increased with the increased moisture content until the moisture content reached 13.78 % and then these parameters decreased with increasing moisture contents above 13.78 %. These results can be explained by antiplastization and plastization effect of water depending on the degree of hydration. Increasing levels of fracture force within 8.80 % to 13.78 % moisture range in vertical position can be interpreted as an evidence of antiplastization effect of water. Above 13.78 % moisture content, the reduction in these parameters indicates the plastization effect of water, and thus explains the decrease in brittleness and the increase in softness of roasted zerun grain. Anti-plasticization effect has been observed in different food systems such as tapioca starch films (Chang et al. 2006), coffee beans (Pittia et al. 2007), extruded flat bread (Marzec and Lewicki 2006), breakfast cereals (Gondek and Lewicki 2006). Energy data at rupture point calculated from Eq. (6) and estimated energy also showed that the increase of the grain moisture content due to the plasticizing effect causes an observable increase in deformation. Therefore, the absorbed energy at fracture point increased in the grains containing moisture over 13.78 % while rupture force was reduced at those moisture levels (Table 2). Similar results were reported for pea by Łysiak (2007). In our study, the highest Weibull modulus m_f calculated from the basis of rupture force data was estimated for 18.55 % moisture content (Table 1). For increasing moisture levels from 8.80 % to 23.40 %, the shape parameter (m_e) calculated from the basis of rupture energy data increased from 2.15 to 3.24. The Weibull modulus (m) represents the scatter in

material strength and if m is large, the scattering becomes smaller (Aarseth and Prestløkken 2003; Łysiak 2007). An increase in the moisture content of roasted grain caused a lower scatter when Weibull modulus (m_e) was evaluated for all moisture content (Fig. 2). This may be explained by an increase in the homogeneity of the roasted grain structure and thus indicates a decrease in brittle breaking at high moisture content.

Conclusions

Analysis of results showed that the physical and mechanical properties of roasted Zerun grain changed with grains' moisture content. The average width, thickness, geometric mean diameter, true density, bulk density, porosity and angle of repose, of roasted grain increased polynomially in the range of moisture contents from 8.80 % to 23.80 %. The knowledge on the physical properties of roasted zerun grains, like those of other grains and seeds would allow the design of equipment and processes for handling, conveying, separation and storing of roasted Zerun wheat and the development of packing processes. Rupture tests under compression showed that the roasted grain was brittle and the rupture force and energy data were adequately represented with the Weibull distribution. Roasting process generate voids of different sizes in grains. Thus, roasted grains are made up of solid particles, liquids and gas. For this reason roasted Zerun wheat is consumed as a popular snack in central Anatolia region of Turkey. However, our analysis using Weibull parameters showed that the increase in moisture content of grains caused the loss of brittleness due to the increased homogeneity of the grain structure.

References

- Aarseth KA, Prestløkken E (2003) Mechanical properties of feed pellets: Weibull analysis. *Biosyst Eng* 84(3):349–361
- Adebowale A-RA, Sanni LO, Owo HO, Karim OR (2011) Effect of variety and moisture content on some engineering properties of paddy rice. *J Food Sci Tech-Mys* 48(5):551–559
- Al-Mahasneh MA, Rababah TM (2007) Effect of moisture content on some physical properties of green wheat. *J Food Eng* 79:1467–1473
- Altuntaş E, Yıldız M (2007) Effect of moisture content on some physical and mechanical properties of faba bean (*Vicia faba* L.) grains. *J Food Eng* 78:174–183
- Aydın C, Özcan M (2002) Some physico-mechanic properties of terebinth (*Pistacia terebinthus* L.) fruits. *J Food Eng* 53:97–101
- Babić L, Babić M, Turan J, Matić-Kekić S, Radojčin M, Mehandžić-Stanišić S, Pavkov I, Zoranović M (2011) Physical and stress-strain properties of wheat (*Triticum aestivum*) kernel. *J Sci Food Agric* 91:1236–1243
- Balasubramanian S, Viswanathan R (2010) Influence of moisture content on physical properties of minor millets. *J Food Sci Tech-Mys* 47:279–284

- Bart-Plange A, Baryeh EA (2003) The physical properties of Category B cocoa beans. *J Food Eng* 60:219–227
- Baryeh EA (2001) Physical properties of bambara groundnuts. *J Food Eng* 47:321–326
- Baryeh EA (2002) Physical properties of millet. *J Food Eng* 51:39–46
- Baryeh EA, Mangope BK (2002) Some physical properties of QP-38 variety pigeon pea. *J Food Eng* 56:59–65
- Chang YP, Abd Karim A, Seow CC (2006) Interactive plasticizing–antiplasticizing effects of water and glycerol on the tensile properties of tapioca starch films. *Food Hydrocolloids* 20(1):1–8
- Coşkun Y, Karababa E (2007) Physical properties of coriander seeds (*Coriandrum sativum* L.). *J Food Eng* 80:408–416
- Dehspande SD, Bal S, Ojha TP (1993) Physical properties of soybean. *J Agric Eng Res* 56:89–98
- Dursun E, Dursun I (2005) Some physical properties of Caper seed. *Biosyst Eng* 92:237–245
- El-Khayat GH, Saman J, Manthey FA, Fuller MP, Brennana CS (2006) Durum wheat quality: some physical and chemical characteristics of Syrian durum wheat genotypes. *Int J Food Sci Technol* 41:22–29
- Fennema OR (1996) Water and ice. In: Fennema OR (ed) *Food chemistry* (3th ed). New York, Basel, Hong Kong, pp 17–95
- Gondek E, Lewicki PP (2006) Antiplasticization of cereal-based products by water. Part II: Breakfast cereals. *J Food Eng* 77:644–652
- Işıklı ND, Yılmaz İ (2011) Some physical properties of sun-dried Berberis fruit (*Berberis crataegina*). *J Food Sci Technol-Mys*. doi:10.1007/s13197-011-0469-y
- Jacobs DR, Steffen LM (2003) Nutrients, foods and dietary patterns as exposures in research: a framework for food synergy. *Am J Clin Nutr* 78(3):508–513
- Jacobs DR Jr, Andersen LF, Blomhoff R (2007) Whole-grain consumption is associated with a reduced risk of noncardiovascular, noncancer death attributed to inflammatory diseases in the Iowa Women's Health Study. *Am J Clin Nutr* 85:1606–1614
- Jensen MK, Koh-Banerjee P, Hu FB, Franz M, Sampson L, Grønbaek M, Rimm EB (2004) Intakes of whole grains, bran and germ and the risk of coronary heart disease in men. *Am J Clin Nutr* 80:1492–1499
- Jha SN (2005) Mathematical simulation of roasting of grain. *J Food Eng* 71:304–310
- Kahyaoglu LN, Şahin S, Sumnu G (2010) Physical properties of par-boiled wheat and bulgur produced using spouted bed and microwave assisted spouted bed drying. *J Food Eng* 98:159–169
- Karababa E (2006) Physical properties of popcorn kernels. *J Food Eng* 72:100–107
- Karaj S, Müller J (2010) Determination of physical, mechanical and chemical properties of seeds and kernels of *Jatropha curcas* L. *Ind Crop Prod* 32:129–138
- Katcher HI, Legro RS, Kunselman AR, Gillies PJ, Demers LM, Bagshaw DM, Kris-Etherton PM (2008) The effects of a whole grain-enriched hypocaloric diet on cardiovascular disease risk factors in men and women with metabolic syndrome. *Am J Clin Nutr* 87:79–90
- Kenghe RN, Nimkar PM, Shirkole SS (2011) Moisture dependent physical properties of lathyrus. *J Food Sci Technol-Mys*. doi:10.1007/s13197-011-0428-7
- Kingsly ARP, Singh DB, Manikantan MR, Jain RK (2006) Moisture dependent physical properties of dried pomegranate seeds (Anardana). *J Food Eng* 75:492–496
- Koh-Banerjee P, Franz M, Sampson L, Liu S, Jacobs D, Spiegelman D, Willett W, Rimm EB (2004) Changes in whole-grain, bran and cereal fiber consumption in relation to 8-y weight gain among men. *Am J Clin Nutr* 80:1237–1245
- Liu RH (2007) Whole grain phytochemicals and health. *J Cereal Sci* 46:207–219
- Łysiak G (2007) Fracture toughness of pea: Weibull analysis. *J Food Eng* 83:436–443
- Mariotti M, Alamprese C, Pagani MA, Lucisano M (2006) Effect of puffing on ultrastructure and physical characteristics of cereal grains and flours. *J Cereal Sci* 43:47–56
- Marzec A, Lewicki PP (2006) Antiplasticization of cereal-based products by water. Part I: Extruded flat bread. *J Food Eng* 73:1–8
- Mohsenin NN (1980) Physical properties of plant and animal materials. Gordon and Breach Science Publishers Inc, New York, pp 51–87
- Nalbandi H, Seiedlou S, Hajilou J, Moghaddam M, Adlipour M (2009) Physical properties and color characteristics of Iranian genotypes of cornelian cherry. *J Food Process Eng*. doi:10.1111/j.1745-4530.2009.00434
- Nalbandi H, Ghassemzadeh HR, Seiedlou S (2010) Seed moisture dependent on physical properties of *Turgenia latifolia*: criteria for sorting. *J Agric Technol* 6:1–10
- Nikoobin M, Mirdavardoost F, Kashaninejad M, Soltani A (2009) Moisture-dependent physical properties of chickpea seeds. *J Food Process Eng* 32:544–564
- Pamies BV, Roudaut G, Dacremont C, Le Meste M, Mitchell JR (2000) Understanding the texture of low moisture cereal products: mechanical and sensory measurements of crispness. *J Sci Food Agric* 80:1679–1685
- Panasiewicz M, Grochowicz J, Sobczak P (2009) Influence of hydro-thermal processes on selected physical properties of oat grain. *J Food Eng* 90:81–89
- Pittia P, Sacchetti G (2008) Antiplasticization effect of water in amorphous foods. A review. *Food Chem* 106:1417–1427
- Pittia P, Nicoli MC, Sacchetti G (2007) Effect of moisture and water activity on textural properties of raw and roasted coffee beans. *J Texture Stud* 38:116–134
- Pradhan RC, Naika SN, Bhatnagar N, Vijay VK (2009) Moisture-dependent physical properties of *Jatropha* Fruit. *Ind Crop Prod* 29:341–347
- Singh KP, Mishra HN, Saha S (2010) Moisture-dependent properties of barnyard millet grain and kernel. *J Food Eng* 96:598–606
- Sobukola OP, Onwuka VI (2010) Effect of moisture content on some physical properties of locust bean seed (*Parkia fillicoides* L.). *J Food Process Eng*. doi:10.1111/j.1745-4530.2009.00511
- Tighe P, Duthie G, Vaughan N, Britten J, Simpson WG, Duthie S, Mutch W, Wahle K, Horgan G, Thies F (2010) Effect of increased consumption of whole-grain foods on blood pressure and other cardiovascular risk markers in healthy middle-aged persons: a randomized controlled trial. *Am J Clin Nutr* 92(4):733–740
- Vilche C, Gely M, Santalla E (2003) Physical properties of quinoa grains. *Biosyst Eng* 86(1):59–65
- Vishwakarma RK, Shivhare US, Nanda SK (2011) Physical properties of guar seeds. *Food Bioprocess Technol*. doi:10.1007/s11947-011-0514
- Wang L, Gaziano JM, Liu S, Manson JAE, Buring JE, Sesso HD (2007) Whole- and refined-grain intakes and the risk of hypertension in women. *Am J Clin Nutr* 86:472–479