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Grading Factors of Wheat Kernels Based on Their Physical Properties

Néstor Ponce-García, Benjamín Ramírez-Wong,
Anayansi Escalante-Aburto,
Patricia I. Torres-Chávez and
Sergio O. Serna-Saldivar

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Abstract

Cereal grains are biological materials and as such have certain unique characteristics greatly affected by both genetics and environment. Wheat is worldwide considered as the main cereal grain in the average human diet. The aim of this chapter is to provide an overview of the most important grading factors and kernel physical parameters that are involved in the estimation of quality specifications. The determination of the physical properties of wheat kernels gives a first approximation of the structural characteristics useful for the design and selection of equipment for handling, harvesting, aeration, drying, storing and more importantly to functionality, processing and end uses. For instance, physical quality test that directly measure those properties are needed. To get a better prediction, physical evaluation of the wheat kernels offers a first and interesting quality control for their selection as raw materials in order to optimize quality of a large diversity of products. Kernel colour, shape, size, sphericity, porosity and bulk and specific densities and damages incurred due to heat, insects, molds or sprouting are relevant tests related to wheat kernel properties and quality.

Keywords: wheat, physical properties, damage, shape-size, volume-weight

1. Introduction

Wheat is one of the three most important cereals worldwide in terms of production and consumption. According to FAOSTAT [1], the estimated annual production in 2014 was 728 million tons, which provided daily 178 g per capita to the average human being. Wheat is considered among the oldest crops and is grown in more than 120 countries around the globe [2] and is the

main cereal in the human diet worldwide due to its agronomic adaptability, storability, nutritional value and diversity of products produced from it [3]. Wheat is unique among grains because its protein mixed with water and mechanical work yields a viscoelastic dough or batter capable of trapping gases produced by yeast or baking powders producing an array of leavened products such as breads, cakes and cookies.

Cereals grains are biological materials that differ in features due to many factors such as cultivar or genotype, soil fertility, growing conditions and agronomic practices [4]. The classification and grading play an important and critical role in the market because assures quality control guidelines. Furthermore, the standardization of grain quality allows a better marketing and grain processing to produce different products. Selected grain types for specific uses relate to their physical properties because they affect chemical composition, functionality and optimum industrial end use. The standardization of grain quality allows process a grain's lot with similar grade or quality [5].

Different methods for the classification of wheat grains are based on growth habit, end use and physical characteristics. The use of these methods can be referred to as technological classification [6]. Wheat-based products require different classes of the grain for their processing. Industrial quality is characterized by physical, chemical and rheological analysis related with roller milled refined flour, used especially in the manufacture of yeast-leavened breads (hard wheat) or chemically leavened cookies and cakes (soft wheat) or to produce semolina to elaborate long and short pasta products (durum wheat).

Physical evaluation of the wheat kernels offers a first and interesting quality control for selection as raw materials because the kernel physical features are related with design of equipment, handling, aeration and storage as well as to end use. Increasingly, analyses are implemented to assess the inherent characteristics of the grain to better know their attributes. The study of wheat kernel characteristics is necessary because new cultivars (with new and different properties) are constantly being bred and produced [7].

This chapter reviews the principal physical properties of wheat kernels in three sections. The first covers aspects related to appearance and damage, the second addresses shape and size features and the third grain volume, weight and density.

2. Wheat physical properties

Different wheat grain properties are included in the grading systems. Quality parameters are related with *stable* properties, that is, grain hardness, size, shape and color; *variable* properties, that is, moisture content, contamination, damage to grain and bulk density and *permanent* properties, that is, fermented and foreign smells and faults that can be rectified [8]. While there is no uniform approach in the wheat industry to estimate the degree of quality, the stable and variable properties have extensive relationships with physical characteristics and provide a primary basis to determine initial grain quality control parameters.

Understanding the physical properties using rapid analysis methods is essential to estimate or predict with an acceptable level of certainty grain quality according to postharvest handling, storage and food processing. The market value of wheat grain is determined by various factors such as kernel morphology, texture, test weight and the shape of germ, crease and brush [9]. El Fawal et al. [10] cited that the physical quality of the kernel plays an important role for identifying the engineering characteristics of cereal crop grains, while Dziki and Laskowski [11] discuss that studies concerning the relationships between wheat kernel physical properties and milling properties have been carried out since the beginning of the cereal processing industry.

There are five main categories of data on physical properties of agro-food materials, which responds to physical treatments involving mechanical, thermal, electrical, optical and electro-magnetic processes [4, 12]. For granular materials as cereal grains, the physical properties are classified by category or purpose, which in turn include more specific quality assessments; some of the major criteria applied to determine wheat kernel physical quality attributes included appearance and damage, size and shape and weight volume and density test, to cited a few of them.

Broadly, the geometric properties such as size and shape are one of most important physical properties considered during the separation and cleaning of kernels [13]. Study of physical properties in wheat kernels used are more complicated due to the inherent relationship among categories, that is, weight volume and density values are dependent on the shape, size and degree of kernel damage. Besides, physical properties of cereal grains are intrinsically linked to its moisture content level.

2.1. Appearance and damage

Appearance is a valuable physical characteristic for selective classification and rating for subsequent handling and processing. It is considered the single most important factor that determines the economic value of a certain lot of grains. A number of grading factors adversely affect the appearance of cereal grains [14]. For purposes of inspection and grading, wheat kernels are considered damaged if the damage is distinctly apparent, therefore recognized as harmful for commercial purposes [15]. More specifically, U.S. Wheat Associates [16] suggested that wheat kernels are damaged if badly ground, weathered, frosted or present heat, insect, mold or sprout damages. The inspection of grain appearance and damaged kernels are recognized to greatly influence wheat kernels quality, because sound kernels could be stored for longer periods of time or processed into better quality intermediate and finished products. A portion of a particular wheat sample is thoroughly examined in order to detect different sorts of damage by physical or biological factors. The most common tests related to quality are presented below.

2.1.1. Color

Color is one of the first and most relevant characteristics related to grain quality. Wheat kernel color depends on the species and other factors and is mainly dictated to chemical components

presents in the ripe seed coat. Bechtel et al. [17] mentioned that color of wheat caryopses varies from light buff or yellow to red-brown according to the absence or presence of red pigmentation in this layer. Wheat is commonly classed according to color as red or white. Sometimes the perception of grain color is affected by the texture of the endosperm since the soft portion presents air-starch and air-protein interfaces that impart the chalky or dull appearance. On the other hand, the absence of voids or microscopic spaces in the endosperm of hard wheat gives a glassy or vitreous appearance resulting in trends of the red coloration present in the seed coat.

Other factors may affect the natural color of kernels such as mold-infestation in the field or during storage, heat or frost damage and other caused by phytopathogens. Shahin et al. [18] reported that mildew growth on wheat kernels reduces grain quality due to the characteristic gray discoloration which negatively impacts color of refined flours.

Computer-aided image analysis has many applications in agricultural sciences. For assessing grain quality this technique is able to objectively determine shape and color. However, problems are encountered in practical applications of these methods because they rarely correlate with the examined attributes and therefore a multivariate analysis is required. Principal component analysis (PCA)—a variant of the above method—is used when a high number of variables have to be reduced to several components [19]. Image analysis is performed by algorithms that use different color, texture and shape features as input parameters [20].

Actually, interest in white wheat kernels by both the milling and baking industries is increasing, because refined and mainly whole grain flours milled are preferred for different products and applications. Hard white wheat has been reported to have distinct advantages over the conventional hard red counterpart. These advantages include higher flour extraction rate and lighter colored end products [21].

2.1.2. Insect damage

One of the most relevant wheat kernel quality parameters is insect damage. This particular assessment is considered one of the most critical degrading factors [22], because it relates to flour yield and color and increases the amounts of insect fragments present in flours and processed products which are considered as one of the most important quality factors related to food sanitation. Presence of insects induces losses in quantity and quality by insect consumption, grain weight loss, contamination (toxicity) with excrement, bodily fragments and chemical secretions that disfavor flour flavor and odor. In addition, insects increase heat and kernel moisture due to their metabolic activity. The potent enzymes produced by insects and by the grain respiration system are known to negatively affect milling and baking qualities [23, 24].

The main group of insects that cause serious damage in cereal grains includes beetles such as *Sitophilus granarius*, *Tribolium castaneum*, *Trogoderma granarium*, *Tenebroides mauritanicus* and *Rhyzopertha dominica*. Primary pests infest sound grain whereas secondary pests can attack only broken or cracked grains or milled products [25]. A large portion of the insect's life is spent inside the kernels; therefore, their detection is extremely difficult. Fortunately, the industry has adopted new techniques for identification of insect damage inside grains using Near

Infrared (NIR) spectroscopy [6]. Needless to say, the internal infestation degrades the quality and value of grains [24].

Pest control begins with a preventive control and disinfection of empty storage containers and storing grain in pest-free conditions. Different improved methods include hermetically closed containers, heating or cooling, ionizing radiation, light and pheromone traps and storage under controlled atmospheres [25]. Postharvest control is essential in many countries and the traditional treatment is chemical fumigation [22]. Unfortunately, the use of synthetic insecticides has problems such as their persistent toxicity, development of resistance in insect populations and other adverse environmental impacts [26, 27].

2.1.3. *Sprouted kernels*

Sprouted kernels are easily detected by visual observation such as kernel swelling, growth in the germ area, discoloration of the germ, the split of the bran over the germ and mainly by the detection of the emergence of the radicle or rootlets and coleoptile or acrospires [6, 28]. Sprouting can occur both, in the field or during storage when kernels absorb moisture and are exposed to appropriate temperature conditions [5]. This germination process involves several biochemical changes in the endosperm of the kernel, such as synthesis and release of amylolytic, lipolytic, fibrolitic and proteolytic enzymes that degrade starch, oil, fiber and proteins, respectively [5, 28]. The presence of sprouted damage level usually is determined quantitatively by measuring the amount of α -amylase using the Falling Number (FN) [29] or by determining peak viscosity with the Rapid Visco Analyser (RVA) [28]. In the industry, different unfavorable technical factors are associated with the use of sprouted kernels such as reducing milling yield and lowering flour quality, sticky doughs and significant effects in the baking quality of bread wheat [6, 28]. Sprouted kernels usually yield darker colors due to the presence of significant amounts of reducing sugars and degraded proteins that upon heating form higher amounts of Maillard reaction products [5].

2.1.4. *Heat damage*

Heat damage in kernels is mainly attributed to two major reasons: first, faulty storage of damp grain and second, as a consequence of an inadequate (high) artificial drying [6]. Grains stored at high moisture-induced elevated respiration rates, consequently metabolic activation of the grain, causing heat, mold growth and possible insect infestation [5]. A darker color in the grain is indicative of heat damage, however sometimes this type of damage is not usually visible and requires testing and it is necessary in most cases to cut the kernels to determine if the color of the cross-section is reddish-brown. Wheat doughs produced from heat-damaged flours are sticky due to the partial degradation of starch granules and gluten proteins by amylases and proteases, respectively. In addition, the bread crumb is darker due to the higher reducing sugars and hydrolyzed proteins that promote browning reactions upon baking. Therefore, the gluten protein and rheological testing are required to evaluate effects of this defect. Heat damaged seeds are usually associated to the loss of viability [5, 6].

2.1.5. Frost damage

The degree of tolerance shown by wheat kernels on the field to low or freezing temperatures depends largely on the stage of development at which the stress occurs. Wheat is most susceptible to frost damage at flowering, being particularly harmful when it occurs during grain filling [6, 30]. Frosted grains are creased along the long axis and creases are regular or uniform, unlike grains with moisture stress in which this anomaly is not uniform. Sometimes, frosted grains will have a blue-gray appearance [30] and usually lower 1000-kernel weight because they did not fill properly [5]. The premature death of the kernel results in less polymeric protein synthesis and consequently their gluten functionality is compromised affecting negatively baking performance [6].

2.1.6. Mold damage

Wheat grains represent an important substrate for the development of different types of molds which affect adversely the grain quality. Serna-Saldivar [5] specifies that the genus *Fusarium*, *Alternaria* and *Penicillium* are the fungus most frequently isolated from wheat infested negatively grains. Growth of fungi in stored wheat affects yield and relevant quality factors such as discoloration, germination, free fatty acid value, falling number and dough rheological properties [31], because molds produce important enzymes such as amylases, proteases and lipases.

Presence of mold in the grain also causes production of undesirable odors and grains infested with *Fusarium* and/or *Aspergillus* will probably contain significant amounts of mycotoxins (secondary metabolites produced by the fungi) that endanger human and animal health [5]. Fungal species that attack cereal grains can be classified into two groups: field fungi (less aggressive) and storage fungi. Temperatures between 30 and 35°C and moisture content in the grain above 15% are the conditions for the optimal development of fungi in storage [31].

2.2. Shape and size

2.2.1. Grain morphology

The wheat grain or kernel—botanically named caryopsis—is a particular dry fruit and indehiscent consisting of three main regions are easily recognizable: pericarp, endosperm and germ (which includes the embryo) [25]. The geometric properties such as size and shape are one of most important physical properties considered during cereal grains processing, due to its morphology can be associated with quality parameters. Grains are considered like spheres or ellipse because of their irregular shapes [13].

Wheat shape can be described as round (approaching spheroid). Morphologically, Evers and Millar [32] describe that wheat kernel presented a marked crease, a re-entrant region on the ventral side, extending along the grain's entire length and deepest in the middle; however, variation occurs in the thickness, large and width of the grain. The shape of the groove is a characteristic feature of some species and cultivars.

2.2.2. Axial dimensions

In a wheat kernel, three principal dimensions are commonly measured: length (L), width (W) and thickness (T) (**Figure 1**), which typically are determined using a micrometer or caliper and reported in millimeters. The principal axial dimensions of grains are useful in selecting sieve separators and for the calculation of extraction rate during size reduction [33]. These measurements can also be used to calculate volume of kernels, which are important during modeling of grain drying, aeration, heating and cooling. The effects of size and surface area on drying rates of particulate materials can also be characterized by using the surface to volume ratio [34]. The kernels at the spikelet had different individual mass. The dimensions of the wheat kernels within a plant varied significantly and the development rates and dimensions of kernels are different [35].

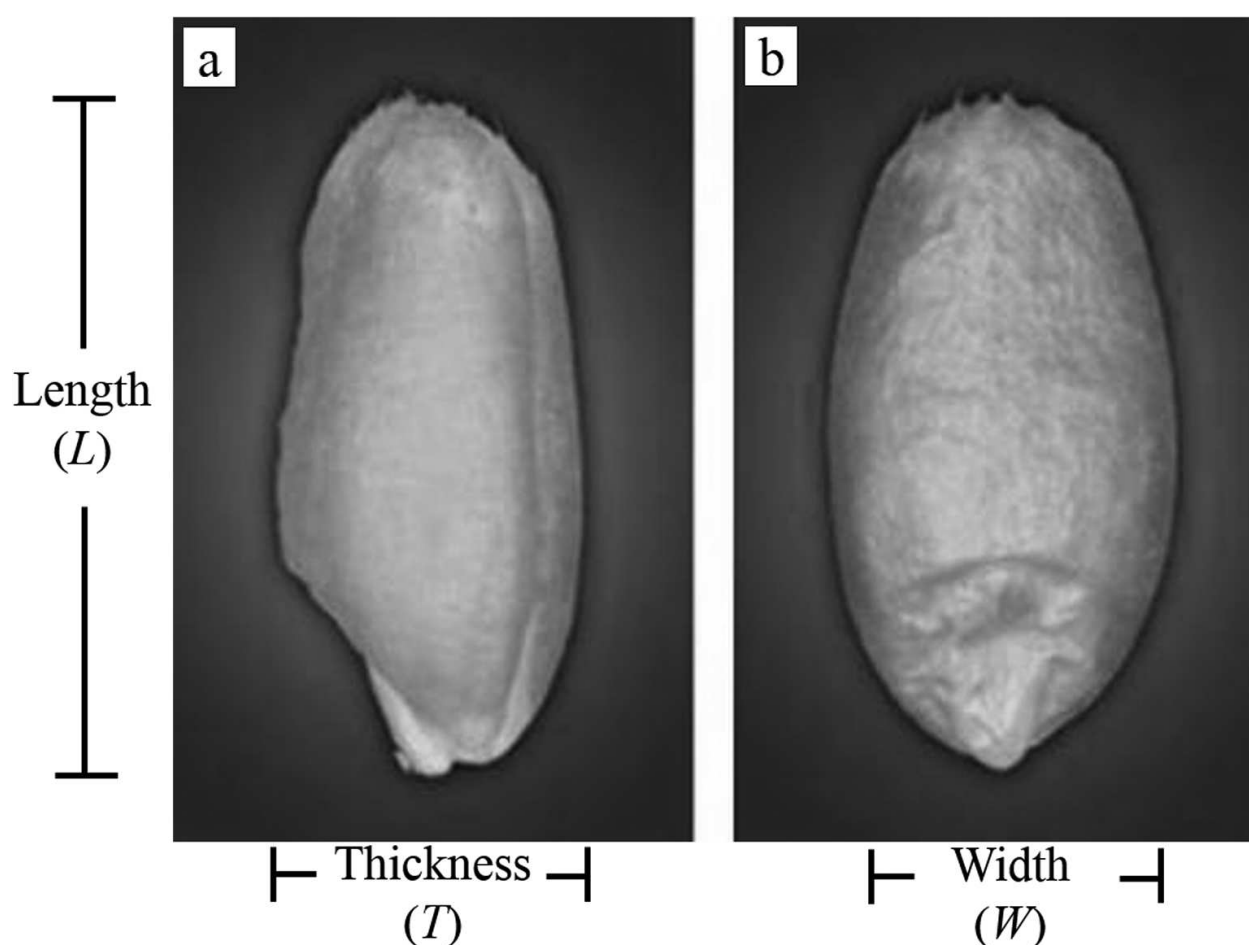


Figure 1. Axial dimensions in a wheat kernel. (a) Length (L) and thickness (T); (b) width (W).

Small kernels are considered to have less potential flour yield and inferior milling properties. Gaines et al. [36] discussed that soft wheat cultivars differed in their average kernel size and in the size distribution of their kernels. However, they found that kernel characteristics, milling performance and soft wheat end-use qualities were not influenced by kernel size, except that small kernels tended to be softer. The milling and baking properties of smaller kernels were

not found to be inferior to larger counterparts, but were equivalents. Aversely, Morgan et al. [37] reported that “in general, as kernel size declines, flour yield and flour refinement (ash and color) are adversely affected”, but agrees that small kernels were softer than large kernels.

Dholakia et al. [9] proposed an interesting factor-form-density (FFD) for phenotypic measurement on wheat kernels from described the differences in the grain structure (density) and the deviation from the cylindrical form, which was compiled as:

$$\text{FFD} = \frac{\text{Kernel weight}}{\text{Kernel length} \times \text{kernel width}} \quad (1)$$

2.2.3. Sphericity

Sphericity (ϕ) expresses the characteristic shape of a solid object relative to that of a sphere of the same volume. The longest diameter (major) and shortest diameter (minor) will adequately describe the size of an ellipsoidal object such as the wheat kernel [4]. Bayram [38] suggested that the determination of the sphericity is usually difficult and not practical, due to irregular shape of the granular material and it is the calculation of the exact volume and surface area, involving multiple length measurements. In this sense, this author proposed a novel and easily model to determine the sphericity of granular materials, following the next expression:

$$\phi_s = \frac{\sum(D_i - \bar{D})^2}{(\bar{D}N)^2}, \quad (2)$$

where ϕ_s = sphericity value, D_i = any measured dimension, \bar{D} = average dimension or equivalent diameter and N = number of measurements. Increase in the N increases the accuracy. In Eq. (2), when ϕ_s for a sphere is 0, that is, an increase in ϕ_s value using Eq. (2) shows the deviation from the sphericity.

2.2.4. Roundness

Mohsenin [39] defined roundness as the measure of the sharpness of the corners of a solid, whereas Curray [40] proposed the next equations for estimating roundness under different conditions of geometry and application:

$$\text{Roundness} = \frac{A_p}{A_c}, \quad (3)$$

where A_p = largest projected area of object in natural rest position and A_c = area of smallest circumscribing circle. The object area is obtained using the next equation:

$$\text{Roundness} = \frac{\sum r}{NR}, \quad (4)$$

where r = radius of curvature as defined in **Figure 2**, R = radius of the maximum inscribe circle, N = total numbers of corners summed in numerator.

$$\text{Roundness} = \frac{r}{R}, \quad (5)$$

where R in this case is the mean radius of the object and r is the radius of curvature of the sharpest corner. The objection to this method is that the radius of curvature of a single corner determines the roundness or flatness (Figure 2).

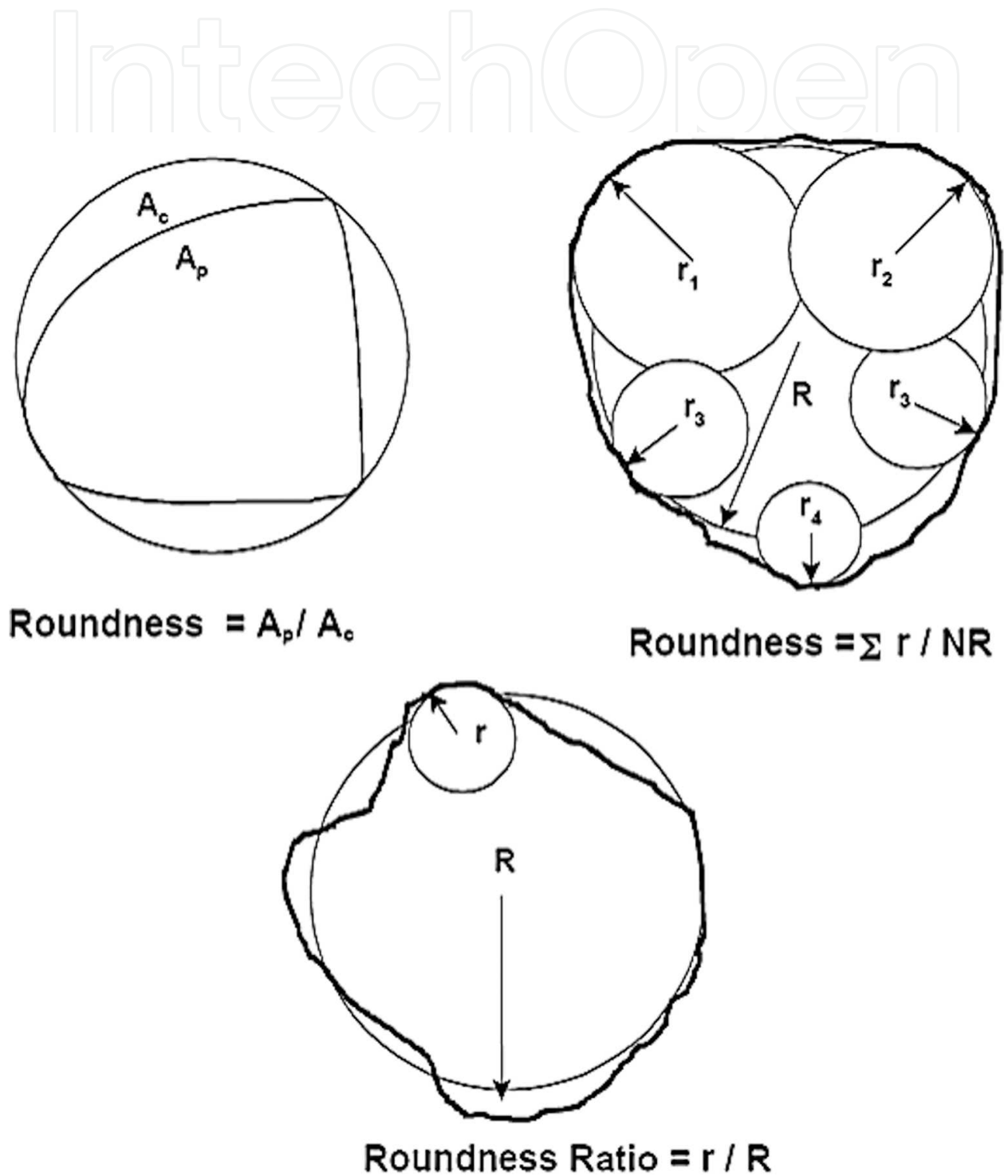


Figure 2. Roundness as defined by geologists to describe shape of grains and pebbles (adapted from Mohsenin, 1978).

Higher values of sphericity and roundness indicate that the shape of the kernel is closer being spherical. It is important to know sphericity and roundness—for example, before handling or dryer process—so that this efficiency increases.

It is important noted that the main influence is not the shape and size *per se*, but the degree of variation in these attributes within a sample [17]. Wheat kernel size, like most of the traits of biological interest and agricultural importance, is a complex character and is suggested to be quantitative in nature, although kernel size and shape have emerged as important breeding objectives [9].

2.3. Volume weight and density

Unit volume weight indicates the density and compactness for a given volume of grain; a minimum test weight requirement is generally one of the primary specifications used in wheat grading and classification [6]. Test weight or density in wheat kernels is a physical quality characteristic considered mainly by flour and semolina millers. In general, high weight (accordance to wheat class) may indicate a grain sample healthy and optimum appearance, whereas low weight can occur as result of one or more adverse events such as insect damage, heat stress or delayed harvesting [41].

Bulk density and true density can be useful for storage facilities, because affect the rate of heat and mass transfer of moisture during aeration and drying process [33]. In addition of these two parameters, porosity can be useful in sizing grain hoppers and storage facilities [42]. In the grain industry, the ratio weight-volume commonly is report in bushels units or kg/hL (100 L) [4]. Test weight per bushel is the weight of the grain required to fill a level Winchester bushel measure 2150.42 in³ (35.24 L) capacity [16]. The conversion factors of pounds per Winchester bushel and pounds per imperial bushel (2219.36 in³) to kg/hL are 1.297 and 1.247, respectively. This test is related to the true grain density, which is affected by grain condition, grain texture and protein content. Wheat kernel sample affected by insect attack, molds or any other damage had a lower test weight when compared with a healthy sample [5].

2.3.1. Bulk density

Space occupying by amount of material per volume unit is call density (ρ) and is expressed in units of mass per unit volume. True density (ρ_t) is defined as the ratio of the volume of particles and can be determined using the water [43] or by gas [33] displacement methods which determine the volume of the sample. Unfortunately simple techniques as water displacement can result in errors especially if the water penetrates into the kernel [39]. In kernel volume (V) exists interstitial air spaces with different values of particle density and bulk density. Particle density is the mass divided by the volume of the particle alone. The mass of a group of individual particles divided by the space occupied by the entire mass (volume) including the air space is bulk density (ρ_b). This could be calculated from the following relation [42]:

$$\rho_b = \frac{W_s}{V_s}, \quad (6)$$

where the ρ_b = bulk density (kg/m^3), W_s = weight of the sample (kg) and V_s = volume occupied by the sample (m^3).

The irregular shape and porous nature of agricultural materials present difficult problems in volume and density measurements. The density of a material has a significant effect on its mechanical characteristics [39]. According to Molenda and Horabik [44], the determination of the bulk density is based on measurement of the mass of a granular material poured freely into a cylindrical container of constant volume, typically 0.25 or 1 dm^3 . Grain density usually varies within a relatively broad range, depending on the species and cultivar, manner of silo, height of deposit, degree of contamination of the grain and other factors. It is recommended to estimate the density of a granular material in a silo by assuming an average density increase of 6% with relation to the density value determined from the mass of 1 hL.

2.3.2. Porosity

Porosity (ε) is the percentage of air between the particles compared to a unit volume of particles [4] and can be calculated from bulk and true density values, using the following relationship proposed by [39]:

$$\varepsilon = \frac{\rho_t - \rho_b}{\rho_b} \times 100, \quad (7)$$

where ε = porosity (%), ρ_t = true density (kg/m^3), ρ_b = bulk density (kg/m^3).

Wheat endosperm is mostly composed of starch granules, protein matrix and pores or air voids. Starch granules are bound to one other by the continuous protein matrix. Topin et al. [45] performed an interesting study in which it was determined that two parameters played a major role in the fracture behavior of the wheat endosperm: the matrix volume fraction ρ^m and the particle-matrix adhesion σ^m . The value ρ^m ranged from 0.04 to 0.2. At $\rho^m = 0.2$, the whole interstitial space is filled with the protein matrix, corresponding to zero porosity. In this sense, these authors suggested that the crack of the endosperm depends more on protein content than on the starch-granule adherence, because "the stress inhomogeneities, which are responsible for the stress concentration factor, are more sensitive to the porosity than to adherence among the constituents".

In grains, low porosity will have greater resistance to water vapor escape during the drying process, which may lead to higher power to drive the aeration fans [33]. The porosity of the bulk is the ratio of the volume of the internal pores within the kernels to its bulk volume [43]. Porosity values in wheat kernels increased slightly as the moisture content increased [42].

2.3.3. Thousand kernel weight

Thousand kernel weight (TKW) measures the mass of the wheat kernel and is an essential parameter for the selection of cultivars with the best physical and physiological seed quality. Generally, higher TKW values are positively related to potential flour extraction or yield [46], because this property is closely related to grain size and proportion of endosperm to germ and pericarp tissues [5]. Wheat breeders and flour millers employ this method as a complement to test weight to better describe wheat kernel composition and potential flour extraction [16]. TKW could be used as an index of wheat milling value and is a good parameter for evaluation of kernels as seed material [11]. When the grain is undamaged may be expected high test weight, due to a greater endosperm to bran ratio [29].

Finally, it is important to highlight that grain moisture content has deep influence on the physical properties, particularly those related with volumetric grain weight and density in bulk as it modifies surface properties of seed-coat as well as the properties of kernel endosperm. Several studies [34, 42, 43, 47] have reported the effect of moisture content on different wheat kernel physical properties and concluded that increasing of moisture content level increased axial dimensions, thousand kernel weight, porosity, kernel volume and sphericity, while bulk density decreased. Higher grain moisture content results in an increase in susceptibility of grains to deformation, thus physical properties of cereal grains vary as a function of moisture content [13, 44].

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Nomenclature

L	Length (mm)
W	Width (mm)
T	Thickness (mm)
FFD	Factor-form-density
ϕ_s	Sphericity (%)
D_i	any measured dimension (mm)
\bar{D}	Average dimension or equivalent diameter (mm)
N	Number of measurements (Eq. (2))
	Total numbers of corners (Eq. (4))
A_p	Largest projected area (mm ²)
A_c	Area of smallest circumscribing circle (mm ²)
$\sum r$	Sum radii of curvature
R	Radius of the maximum inscribe circle (mm) (Eq. (4))
	Mean radius of the object (mm) (Eq. (5))

r	radius of curvature of the sharpest corner (mm)
ρ	Density (kg/m^3)
ρ_t	True density (kg/m^3)
V	Kernel volume (mm^3)
ρ_b	Bulk density (kg/m^3)
W_s	Weight of the sample (kg)
V_s	Volume occupied by the sample (m^3)
ε	Porosity (%)
ρ^m	Matrix volume fraction
σ^{pm}	Particle-matrix adhesion
TKW	Thousand kernel weight

Author details

Néstor Ponce-García^{1,4}, Benjamín Ramírez-Wong^{2*}, Anayansi Escalante-Aburto³,
Patricia I. Torres-Chávez² and Sergio O. Serna-Saldivar⁴

*Address all correspondence to: bramirez@guaymas.uson.mx

1 Faculty of Agricultural Sciences, Autonomous University of Mexico State, UAEM, Toluca, Estado de México, México

2 Research and Graduate Studies in Food Department, University of Sonora, Hermosillo, Sonora, México

3 Nutrition Department, Health Sciences Division, University of Monterrey, San Pedro Garza García, NL, México

4 Center of Biotechnology FEMSA, School of Engineering and Sciences, Tecnológico de Monterrey, Monterrey, NL, México

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