Some physical properties of Australian *Nonpareil* almonds related to bulk storage

Zheng Dingke[1*], John Fielke[2]

(1. *College of Engineering, South China Agricultural University, Guangzhou 510642, China;*
2. *Barbara Hardy Institute, School of Engineering, University of South Australia, Mawson Lakes, SA 5095, Australia*)

Abstract: The Australian almond industry desires to improve storage of harvested almonds awaiting processing. The present work quantified some storage-related physical properties of almonds. The sample used in the study was *Nonpareil* almonds with a kernel moisture content of 4.5% d.b. The mass composition of the sample was 55% hull, 32% kernel and 13% shell. Tests showed that the bulk stored in-shell almonds had only 41% of the volume of in-hull almonds and 45% of the mass. Thus removing hulls before storage would result in saving both storage and subsequent transportation costs. Tests simulating various storage heights of almonds showed that a 10 m storage height of almonds increased the bulk density of in-hull almonds from 320 to 355 kg/m^3, of in-shell almonds (hull removed) from 356 to 378 kg/m^3, and kernels (hull and shell removed) from 604 to 649 kg/m^3. A 10 m storage height of almonds reduced the porosity of in-hull almonds from 67% to 64%, of in-shell almonds from 58% to 55%, and of the kernel from 48% to 44%. Observation showed that the change in bulk density and porosity occurred in an exponential manner with fitted curves that provided R^2 between 0.97 and 0.99.

Keywords: almond, storage, bulk density, true density, porosity, kernel, in-hull, in-shell
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1 Introduction

Almonds are edible seeds. In Australia, almonds are grown principally in the dry climate of South Australia[1]. When almonds on the trees are partly dried, they are harvested mechanically by shaking the tree. The fallen almonds are left to dry on the ground for approximate 7-14 days (until they reach a kernel moisture content less than 6%), and then collected and placed in large stockpiles for storage. As processing rates allowed, they are taken to processing facilities to be hulled and shelled, cleaned, size graded and made ready for sale.

In Australian almond growing regions, there is often rain during the almond harvest period from February to April, and if rain falls on almonds whilst lying on the ground, staining of kernels and growing of mould may result. If almonds are picked up too soon and still have a kernel moisture content greater than 6%, when stored in stockpiles, there is an increased likelihood of mould growth during storage[2]. But quality could still be maintained if the industry uses aerated storage and dehydration after collecting almonds with kernel moisture higher than 6%.

The design of dehydration and aerated storage facilities requires an understanding of the physical properties of the material being stored[3,4]. Important properties are bulk density and porosity[5-7]. Variations in porosity depth will affect the resistance to airflow

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Biographies: John Fielke, BEng, MESc, PhD, Associate Professor, research interests: tillage, seeding, spraying and harvest equipment; post harvest processing of grains and fruit. Email: John.Fielke@unisa.edu.au
***Corresponding author: Zheng Dingke**, PhD., Associate Professor, research interests: Tillage, seeding, cultivation and harvest equipment. Mailing address: Wushan Rd., Tianhe Dist., Guangzhou, 510642, P. R. China. Email: hawkkevin@sina.com. Tel: +86-20-85286120.

through the bulk almonds[8].

The bulk density of biomass is dependent upon material composition, particle shape and size, orientation of particles, true density of individual particles, particle size distribution, moisture content and applied axial pressure[9,10]. There are publications on some physical properties of almonds and the relationship with moisture content, e.g. *Aydin* (2003) who studied the bulk density, true density, porosity, projected area and terminal velocity of Turkish almonds with moisture ranged from 2.77% to 24.97% d.b. [11].

To complement past work, this work investigated the properties of Australian *Nonpareil* almonds and the relationship of their bulk density and porosity with stockpiling height. The *Nonpareil* almond was selected since it is the major variety grown in Australia. As the height of stored produce increases, the axial pressure on the produce at depth will increase and thus will affect its bulk density and porosity.

The main objective of this study was to determine some physical properties of *Nonpareil* almonds such as true density and bulk density of in-hull, in-shell and kernel almonds, and to develop suitable models to describe the variation in bulk density and porosity of in-hull, in-shell and kernel almonds with different stockpiling heights. The data will help estimate variations in airflow resistance and assist in the design of aerated bulk almond storage and dehydration facilities.

2 Materials and methods

2.1 Sample preparation

For this study, almonds (*cv. Nonpareil*), harvested near Renmark, South Australia during summer 2011, were used for experiments. The moisture content was measured by oven drying at (103±2)°C[12]. Moisture contents of kernel, shell and hull were 4.5%, 8.8% and 16.6% d.b., respectively.

This work evaluated almonds which were in forms of in-hull (hull and shell were not removed), in-shell (hull removed) and kernel (hull and shell removed) almonds, and in-shell includes in-sealed-shell (the shell is not opened) and in-opened-shell (shell is opened).

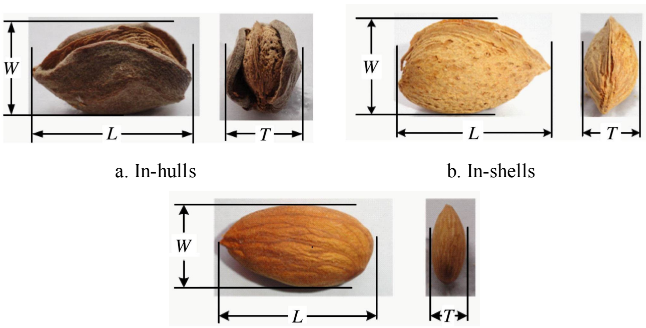
A total of 60 kg samples of in-hull almonds randomly selected from a total bulk of 200 kg were used for the tests. Samples were prepared manually in three categories of in-hull, in-shell and kernel. All in-hull almonds were cleaned to remove foreign matter such as soil and stones, as well as immature fruit. The in-shell and kernel almonds were attained by manually removing the hulls and/or shells, respectively. The in-shell almonds were divided into those with a sealed shell and those with an opened shell. The hand cracked, kernel sample had no damage such as broken, chipped or scratched kernels. Images of the almonds tested are shown in Figure 1.

a. In-hulls b. In-shells

c. Kernels

Figure 1 Almond samples

The sizes variation of the almonds were measured with a digital vernier caliper (0.01 mm accuracy) for the parameters shown in Figure 2 of length (*L*), width (*W*) and thickness (*T*) of in-hulls, in-shells and kernels. Twenty kilograms (20 kg) of in-hull almonds were randomly selected and measured for each parameter. The findings are shown in Table 1.



a. In-hulls b. In-shells

c. Kernel

Note: *W*: width, *L*: length, *T*: thickness.

Figure 2 Almond size parameters

Table 1 The sizes of *Nonpareil* almonds

Characteristics		In-hull	In-shell	Kernel
Width /mm	Range	16.13 - 29.20	13.85 - 25.78	11.38 - 14.58
	Mean ± Std.D (C.V.)	22.04 ± 2.23 (10.1%)	19.78 ± 2.03 (10.3%)	12.97 ± 0.71 (5.4%)
Thickness /mm	Range	12.69 - 37.32	10.05 - 19.40	7.38 - 10.04
	Mean ± Std.D (C.V.)	22.31 ± 4.77 (21.4%)	13.40 ± 1.26 (9.4%)	8.64 ± 0.57 (6.5%)
Length /mm	Range	25.74 - 40.89	23.89 - 36.81	19.52 - 27.39
	Mean ± Std.D (C.V.)	34.65 ± 2.84 (8.2%)	31.38 ± 2.74 (8.7%)	24.16 ± 1.51 (6.2%)

Note: * Std.D = Standard deviation and C.V. = Coefficient of variation.

2.2 Mass proportion of hull, shell and kernel of almonds

The mass proportions of hull, shell and kernel of the almonds were obtained by hand cracking and sorting 35 kg of in-hull almonds into the categories of hull, shell and kernel and then calculating their mass ratios.

2.3 True density

The true density of an almond is defined as the ratio of the mass of the almond to its volume, and was determined by the following formula[3] :

$$\rho_t = \frac{W}{V_p} \tag{1}$$

where, ρ_t is the true density of almond sample, kg/m^3; W is the mass of almond sample, kg; V_p is the bulk volume of almond sample, m^3.

The mass of the almond sample was determined using digital scales with an accuracy of ±0.001 g.

Often, the void volume of a product is measured by a water or aqueous displacement method[11,14-16]. This method is not suitable for measuring the volume of almond samples as they may float and absorb water. As an alternative, an air comparison pycnometer built at UniSA (shown in Figure 3) was used to measure the volumes of almond samples. An air comparison pycnometer was used by Day (1964) who measured the porosity of hay packed to various bulk densities[17], Thompson et al. (1967) who measured the porosity of various seeds and grains[18], and Diehl et al. (1988) who measured the volume of live quail[19].

The pycnometer used had two chambers (see Figure 4); a reference chamber and a sample chamber. Firstly, the empty reference chamber was pressurized, the almond sample under test was placed at atmospheric pressure into the sample chamber. The two chambers were then joined by opening Valve 2 and the pressure allowed to equalize between the two chambers. By knowing the initial and final pressures using a pressure transducer, the volume of the almond sample placed in the sample chamber was calculated as:

$$V_S = V_{2e} - P_r \cdot V_1 \tag{2}$$

where, V_s is the true volume of the sample, m^3; V_{2e} is the volume in the empty sample chamber plus hoses between Valves 2 and 3; P_r is the ratio of initial to final pressure; V_1 is the volume of the reference chamber plus hoses between Valves 1 and 2.

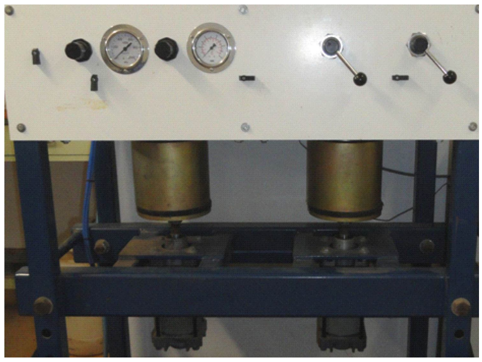


Figure 3 Air-comparison pycnometer

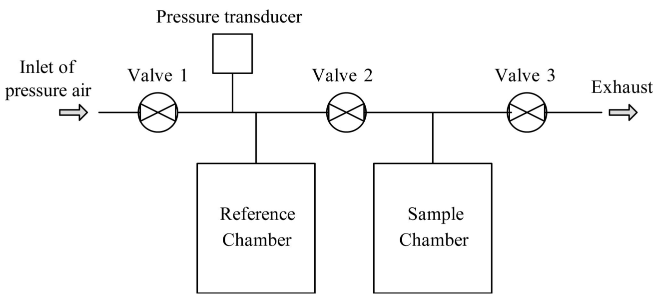


Figure 4 Schematic diagram of an air-comparison pycnometer

The tests were replicated three times for each sample of in-hull, in-shell (sealed shell), in-shell (opened shell) and the kernel. Sealed and split in-shells were examined to measure the effectiveness of shell seal. Tests were also conducted to gain the true density of the hulls and shells.

2.4 Bulk density

Bulk density is the ratio of the mass of a sample to the volume occupied by the sample as poured into a container[6,11,20,21]. The ASABE Standard S269.4, 2010 states that the bulk density of a product should be determined by placing the product into a cylindrical container which is 380 mm in diameter and 495 mm in height[22]. It assumes that the bulk density is constant within the container. In this experiment, the bulk density of almonds was measured using a clear cylinder of 189 mm diameter and 600 mm in height. The density was assumed to be constant over this height of sample. Bulk density of the almond samples was determined as follows:

$$\rho_b = \frac{W}{V_s} \tag{3}$$

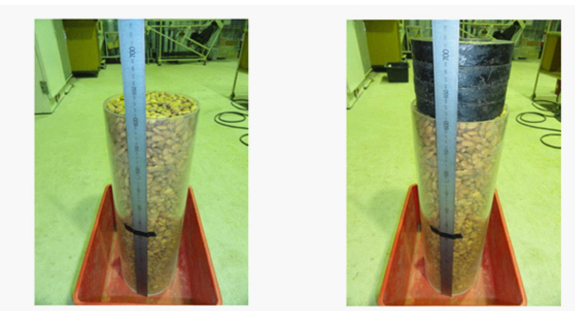
where, ρ_b is the bulk density of the almond sample, kg/m^3; V_s is the true volume of the almond sample, m^3.

According to the definition of static pressure, the pressure at the bottom is in proportion to the height of almonds. The pressure on the almond from a mass above is calculated by the following formula:

$$P = \rho_b \cdot g \cdot h \tag{4}$$

where, P is the pressure on the almonds from weight above, kPa; g is acceleration of gravity, m/s^2; h is the height of almonds, m.

A bulk density test was undertaken by pouring almonds from a height of 150 mm above the top edge of the container at a constant rate with no additional compaction applied (Figure 5a). As per ASAE S269.4 (2010) [22], the almonds which had more than one half of their volume above the top edge of the container were removed, but those almonds with more than one half their volume below the top edge of the container should be left in the container. The mass of almonds placed in the container was weighed using a digital scale to an accuracy of 0.1 g.



a b

Fig.5 Measuring bulk density with different stockpiling height

A weight of 4.5 kg was then placed on the almonds in the cylinder in order to simulate an extra height of almonds above. The sample was allowed to settle for at least three minutes and the sample height in the container was measured to an accuracy of 0.5 mm (see Figure 5b). After recording the height, another weight was then added and the measurement repeated. During loading, the weight was carefully placed on the samples to avoid any impact on the sample. Once the height change of the sample in the container was less than 2 mm before and after addition of a weight, the test was regarded as finished. For each sample the loading test was repeated five times.

2.5 Porosity

Porosity indicates the degree of voidness of a bulk material[3,21] and is a function of the true density and bulk density using the relationship given by Mohsenin (1986) and Thompson et al. (1967) as follows[3,18]:

$$\varepsilon = 1 - \frac{\rho_b}{\rho_t} \tag{5}$$

where, ε is porosity, %; ρ_b is bulk density of almonds, kg/m^3; ρ_t is true density of almond sample, kg/m^3.

3 Results and discussion

3.1 True densities of almonds and its components

Table 2 shows the results of true densities of in-hull, in-sealed-shell, in-opened-shell, kernel, hull pieces only and shell pieces only. The coefficients of variance (*C.V.*) for all samples were low. The results indicated that the density of shell was much less than that of hulls and kernels. The hull was thick and leathery, the shell was hard and woody, and the kernel was hard and brittle with a high proportion of fat and protein[23]. The tests showed that the true density of the in-sealed-shell almond was 1.4% less than that of the in-opened-shell almond. This confirmed that the sealed shells are impermeable to air and that there is a space between the kernel and shell. An air gap between the kernel and shell was also evident as the kernels rattled in their shells when shaken. This result shows that the presence of sealed and unsealed shells in a stockpile will have a small effect on stored almond porosity. In this study, the true density of in-sealed-shell almond was used for further calculations.

Table 2 Results of true densities of almonds

Material	Moisture content/%	Minimum /kg·m^{-3}	Maximum /kg·m^{-3}	Mean /kg·m^{-3}	Std. Deviation	C.V. /%
In-hull	-	946.1	1006.3	977.06	17.59	1.80
In-sealed-shell	-	823.7	838.3	832.04	5.14	0.62
In-opened-shell	-	818.4	823.9	820.68	1.92	0.23
Kernel	4.5	1128.2	1198.2	1165.14	22.19	1.90
Hull	8.8	737.1	848.7	802.06	35.95	4.48
Shell	16.6	410.4	494.2	458.23	30.56	6.67

In comparison to other almond density measurements, Aydin (2003) reported that the true density of a re-wetted Turkish variety of in-shell almond at moisture contents from 2.77% to 24.97% d.b. varied from 1 015 to 1 115 kg/m^3, which was much more than that of Australian *Nonpareil* almonds[11]. The hull density of a re-wetted Turkish almond was (1180±10) kg/m^3 at the moisture content of 2.77% db, which was also much more than that of this study[11]. Rasouli et al. (2010) reported that the true densities of ten cultivars of Iranian in-shell almonds ranged from 790 kg/m^3 to 1 260 kg/m^3 at kernel moisture content from 1% to 6% (w.b.), which were in the range of this work[16].

3.2 Bulk densities and porosities of almonds and its components

Table 3 shows the bulk densities and porosities of in-hull, in-shell and kernel almonds when placed loosely in the test container. Aydin (2003) reported that at moisture contents from 2.77% to 24.97% d.b. of a re-wetted Turkish variety of almonds, bulk densities of kernels ranged from 655 to 525 kg/m^3, respectively[11], which were in the range of the results of this investigation. Rasouli et al. (2010) reported that at the in-shell moisture content from 1% to 6% (wb), bulk densities of ten cultivars of Iranian in-shell almonds ranged from 280 to 480 kg/m^3, and porosities from 48% to 75%, respectively[16], which were in the range of the results of this study.

According to these results, storages volumes required are 3.13 m^3 per 1 000 kg of in-hull almonds, 2.80 m^3 per 1 000 kg of in-shell almonds and 1.66 m^3 per 1 000 kg of almond kernels.

Table 3 Bulk density, true density and porosity of almonds

Characteristics		In-hull	In-shell (sealed)	Kernel
ρ_b /kg·m^{-3}	Mean ± Std. D (C.V)	319.6 ± 3.7 (1.16%)	356.2 ± 5.4 (1.52%)	604.4 ± 2.9 (0.48%)
ρ_t /kg·m^{-3}	Mean ± Std. D (C.V)	977.06 ± 17.6 (1.8%)	832.04 ± 5.14 (0.62%)	1165.14 ± 22.19 (1.9%)
ε/%	Mean ± Std. D (C.V)	67.3 ± 0.38 (0.56%)	57.2 ± 0.65 (1.14%)	48.1 ± 0.25 (0.52%)

Note: * Std.D = Standard deviation and C.V = Coefficient of variation.

3.3 Mass proportions of almond components

The mass proportions of hull, shell and kernel of the batch of almonds examined are shown in Figure 6. The results indicated that 55% of the mass of the in-hull almonds was hull. Based on bulk densities, 1 m^3 of in-hull almonds (containing 102 kg of kernels) when having their hulls removed will only have a volume of 0.41 m^3 of in-shell almonds and then if their shells were removed would require only 0.17 m^3 for the kernels (17% of the volume when stored as in-hull). If the hull can be removed on-farm during harvesting and returned to the orchard, it would have the benefit of reducing storage volume by 59% and transported mass by 55%, thus significantly reducing the storage and transport costs plus having the benefit of being able to return the nutrients contained in the hulls back into the orchard. Leaving the shell on the kernel provides protection for the kernel during handling.

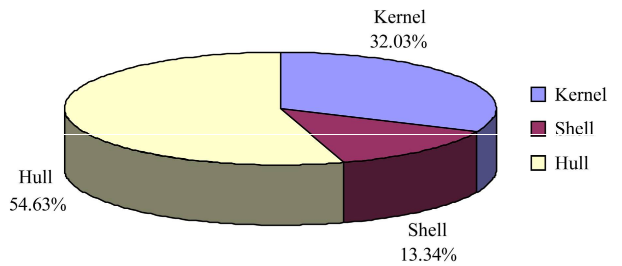


Figure 6 Mass proportions of hull, shell and kernel in an almond

3.4 Relationships of bulk density and porosity of almonds with different heights of almond stockpile

Figures 7 and 8 show the experimental results of bulk densities and porosities for different stockpiling heights, respectively. The results were able to be modeled with the following exponential formulas:

$$\rho_d = \rho_0 + A_m \cdot (1 - e^{-B \cdot h}) \tag{6}$$

$$\varepsilon_d = \varepsilon_0 + \Phi \cdot e^{-C \cdot h} \tag{7}$$

where, ρ_d is the bulk density of almonds at depth of h, kg/m^3; ρ_0 is the bulk density of almonds at the surface, kg/m^3; ε_d is the porosity of almonds at the depth of h, %; ε_0 is the porosity of almonds at the surface, %; A_m, B, Φ and C are model fitting constants.

The results indicated that with increasing stockpiling height, the bulk densities of in-hulls, in-shells and kernels at the base increased at a reduced rate and ended with a steady-state value which was 354 kg/m^3, 379 kg/m^3 and 649 kg/m^3 in the heights of 8.5 m, 8 m and 6 m, respectively. The porosities decreased with height, at a reduced rate and had minimum values of 63.7%, 54.5% and 44.3%, respectively. Figures 7 and 8 indicated that bulk density and porosity of kernels reached a stable value at a shallower depth than those of in-hulls and in-shells which can be explained by the kernels being more rigid.

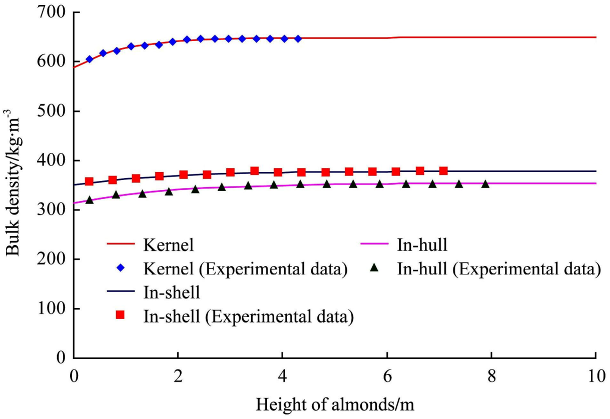


Figure 7 Experimental and modeled results of bulk densities for different heights of almonds

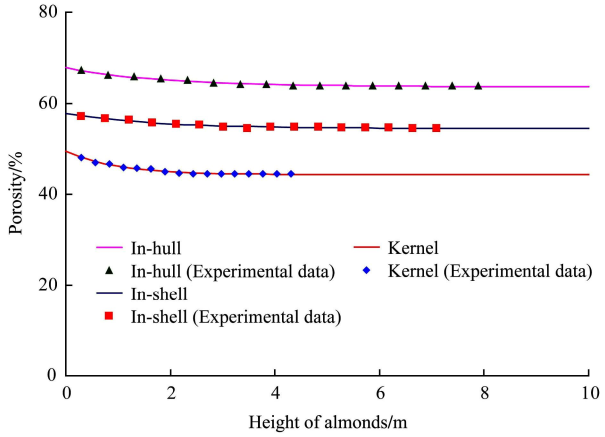


Figure 8 Experimental and modeled results of porosities for different heights of almonds

Coefficients for the parameters in Equations (6) and (7) from all tests are presented in Table 4 and Table 5, respectively. As porosity will affect the easiness of airflow through a stockpile, the results of Figure 8 show that the composition of the product in the stockpile (proportion of in-hull and in-shell) will affect porosity along with a lesser effect from the pressure on the almonds from the height of almonds above.

Table 4 Model coefficients for bulk density of almonds

Material	ρ_0/kg·m^{-3}	A_m	B	R^2
In-hull	313.59	40.830	0.550	0.985
In-shell	350.75	27.708	0.560	0.970
Kernel	588.76	60.008	1.043	0.987

Table 5 Model coefficients for porosity of almonds

Material	ε_0/%	Φ	C	R^2
In-hull	0.637	0.042	0.550	0.985
In-shell	0.545	0.033	0.560	0.970
Kernel	0.443	0.052	1.044	0.987

4 Conclusion

Physical properties of almonds are key parameters for estimating airflow resistance in the design of a bulk almond aeration storage and dehydration facility. The measurement of the mass proportion of hull, shell and kernel of *Nonpareil* almonds grown in South Australia showed that the hull accounted for 55% of the mass of almond that was stored after harvest, and if the hull was removed before storage their volume could be reduced by 59%. Hence, on-farm dehulling would provide considerable savings in storage room and subsequent transportation. The testing of various components of almonds with different levels of compression that simulated the height of almonds when placed in a stockpile showed that at the base of the stockpile the bulk density increased and the porosity reduced with increasing height of product. An exponential model was found to fit the measured data well. The test results showed that with placing of a 10 m height of almonds in stockpile the porosity was reduced from 67% to 64% and from 57% to 55% for in-hull and in-shell almonds, respectively.

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