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New methods for measuring surface area, seed coat separation, and 'chip and scratch' damage in almonds

Megan Fisklements, Diane M. Barrett *

Department of Food Science and Technology, University of California, One Shields Avenue, Davis, CA 95616-8598, USA

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ABSTRACT

This study quantified partial seed coat loss from almond kernels. Basic physical properties of Nonpareil, Monterey, and Butte–Padre kernels were measured to determine which correlate to surface area, and could therefore predict it. Rehydrated almonds were manually peeled and images of seed coats were digitally analyzed. Surprisingly, individual dimensions (length, width, thickness) did not increase with increasing surface area, nor they did scale in proportion to one other. Almond surface area is often estimated from an equivalent sphere, but the sphere-based estimate only predicted 60% of the variation in measured surface area. An empirical model was created to predict surface area (r^2 = 0.74), based on the almond variety, as well as length, width, and mass after rehydration. By comparing the predicted total surface area and the measured surface area of any remaining seed coat, a quantitative percentage of lost seed coat can be calculated.

1. Introduction

California produced almost 1.7 billion pounds of almonds [*Prunus dulcis* L., syn. *Prunus amygdalus*, *Amygdalus communis* L.] in 2010, earning nearly $2.7 billion (Boriss, 2011). The price per pound depends strongly on the USDA grade, which sorts almonds according to incidence of defects. 'Chip and scratch' is an important defect defined as the aggregate exposure of nut meat greater than ¼ in. in diameter (Almond Board of California, 2009). This defect often results from mechanical damage accrued during removal of the almond hull and shell.

Chip and scratch counts rose in the 2008 California crop, with some lots reportedly having as high as 60–70% of almonds exhibiting chip and scratch after roasting. Mechanical damage incurred during removal of the hull and shell would typically affect both the seed coat and the kernel. However, unlike the huller–sheller mechanical damage seen in previous years, the almond nutmeat appeared intact in this new type of chip and scratch; damage was limited to the seed coat, which slipped away from the kernel. Members of the almond industry call this phenomenon 'skin slip' to differentiate it from the almond kernel damage typical of the chip and scratch defect, although it grades the same way, since a portion of the seed coat (skin) is missing in both cases. Better understanding of seed coat adherence could therefore lead to improved product quality and reduced economic losses, since almonds with extensive chip and scratch (with or without kernel damage) may sell for 20–30% less than almonds with intact seed coats.

The USDA 'chip and scratch' defect rating is currently determined using qualitative methods; almonds are considered defective if they have 0.25 in. in diameter (32.15 mm^2) aggregate seed coat missing, irrespective of the source of the damage: chips, scratches, skin slip, or a combination thereof (Almond Board of California, 2009). Rather than using the USDA's qualitative threshold, a method for quantifying the degree of seed coat missing from individual almonds would assist with more accurately measuring and characterizing the chip and scratch defect, no matter the cause.

There is currently no validated protocol for measurement of the actual surface area of an almond. Mohsenin's review of surface area determination (Mohsenin, 1978) included work by Baten and Marshall, showing that the surface area of unpicked apples could be adequately but sub-optimally estimated based on their transverse diameters, i.e. perpendicular to the core in several planes (Baten and Marshall, 1943). Mohsenin also reported on Frechett's research into heat transfer in apples that correlated actual apple surface area (measured by peeling) to the surface area of an equivalent sphere of identical mass and density (Frechette, 1966). Calculating density requires determination of volume, which was measured through volumetric displacement. Building from these, others have more recently posited that the surface area of a pine nut or almond is

* Corresponding author. Tel.: +1 530 752 4800.
E-mail addresses: maclements@ucdavis.edu (M. Fisklements), dmbarrett@ucdavis.edu (D.M. Barrett).

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adequately modeled by a sphere of equivalent diameter as that of a nut, using a geometric mean diameter (length × width × height)$^{1/3}$ (Ozguven and Vursavus, 2005; Ledbetter and Sisterson, 2010).

This change from modeling based on a sphere of equivalent volume to one of equivalent diameter presumably occurred because diameters can be measured faster and with less difficulty than volumes. The substitution of average diameter for volume relies on the intuitive yet untested assumption that almond volume and dimensional properties scale together. Surface area estimation based on a sphere with equivalent diameter reportedly correlates to almond mass with an $r^2 = 0.971$ (Ledbetter and Sisterson, 2010), but this only verifies that mean diameter and mass scale together. No studies validating the assumed correlation between diameters and surface area are found in the literature.

An accurate surface area estimate for almonds is vital to mass transfer calculations such as dehydration and rehydration rates, heat transfer, and drag force (Bayram, 2011). Another application for surface area was proposed by Ledbetter and Sisterson, who suggested that the regression slope of mass versus surface area could potentially be used as an objective varietal standard in order to quantitatively determine the variety of any given almond kernel (Ledbetter and Sisterson, 2010). Such objective varietal standards do not yet exist, so they would be of significant interest to the almond growing and processing industries. Furthermore, the sphere-based surface area estimate does not provide a way to measure how much of the seed coat is missing. Therefore a validated method of quantifying total and missing almond surface area is needed. The aim of this research is to evaluate surface area estimation based on a sphere of equivalent diameter, and to propose a method for quantifying both the total surface area, and the missing seed coat that separates from almonds, as occurs during the defect of chip and scratch.

2. Methods and materials

2.1. Raw materials

Nonpareil, Monterey, and a mixture of Butte and Padre almonds from the 2009 crop were contributed by Paramount Farms and the Almond Board of California. The Agricultural Marketing Service ruled in 2004 that Butte–Padre mixed lots can be handled, marketed, and inspected as one variety because of the very similar characteristics (Service, 2004), so mixed lots of Butte–Padres were used in these experiments. Nonpareil, Monterey, and Butte–Padre varieties were chosen as samples because together they accounted for 64% of the crop, by tonnage, during the period of this study (Almond Board of California, 2010, 2011). Almonds were obtained from three processor lots per variety, each of which contained kernels pooled from dozens of ranches.

Nonpareils from the 2010 crop were obtained from the University of California, Davis Plant Sciences Department. Additional 2010 Nonpareils were hand-harvested from commercial fields. Nonpareil almonds were also purchased from a local grocery store. Double kernels, insect damaged nuts, and almonds with damaged seed coats were excluded from these studies.

The different seed lots, whether hand-harvested or obtained from processor lots, cannot be considered statistically representative of their varieties because they were not grown adjacent to each other within the same field under the same growing conditions. Therefore any differences between these seed lots cannot be claimed to definitively typify comparative varietal differences.

2.2. Surface area modeling

A preliminary dataset ($n = 343$) was assembled in 2009–2010 in order to assess the sphere-based surface area estimation commonly used in the literature. This data set was used in preliminary modeling to screen a large number of potentially important indicators of surface area of intact almonds not exhibiting chip and scratch. It is vital to first establish the total expected surface area in order to later evaluate its absence. Once the best correlates were identified, the model was repeated with a final larger dataset ($n = 811$) of almonds with intact seed coats in order to increase precision. Statistical validity requires that an empirical model be tested on different samples than those that were used in the model creation. Therefore a separate dataset of Butte–Padre and Nonpareil almonds ($n = 510$) was used to validate the model and test its accuracy at quantifying fractional missing seed coat. This final dataset was intended to mimic missing seed coat as occurs in almonds exhibiting chip and scratch defect.

2.2.1. Data collection for preliminary modeling of intact seed coats

Length, width, thickness, mass, volume, and surface area were measured in 72 Monterey almonds, 139 Nonpareil almonds, and 132 Butte–Padre almonds. Volume was measured in 91 of the 139 Nonpareils. The total number or almonds evaluated for each variety was dictated by contributions from collaborators. Length (longest dimension), width (middle dimension), and thickness (smallest dimension) of the almonds were measured with digital calipers. Volume was determined by immersing one almond at a time into a 5 mL beaker completely full of corn oil, and weighing the amount of oil displaced when the almond was added. Displaced oil was weighed instead of measuring it volumetrically in a graduated cylinder because higher precision can be achieved by weighing the displaced liquid. Previous authors used toluene as the displaced fluid (Mohsenin, 1978; Aydin, 2003), but corn oil was utilized in this study due to its non-toxic nature, similarly low surface tension, and higher density. The masses of displaced oil were converted to volume using a corn oil density value of 0.922 g/cm^2.

Geometric mean diameter, density and sphericity were calculated from the following equations (Mohsenin, 1978):

Geometric mean diameter = (Length × Width × Thickness)$^{1/3}$
Density = mass/volume
Sphericity = [(geometric mean diameter)/length] × 100

Surface area could hypothetically be quantified by removing and measuring the seed coat of an almond. Attempts to remove the seed coats of dry almonds were unsuccessful. However, almonds could be manually peeled after soaking in water (imbibition) overnight (Gradziel, 2009). Almond lengths, widths, thicknesses, masses, and volumes were measured again after imbibition in cold (4 °C) distilled water and before peeling. In cases where the volumes were measured before and after imbibition, corn oil was removed from the almond surface with a solution of diluted dish soap (Proctor & Gamble, San Ramon, CA) to remove any barrier to water absorption, and almonds were imbibed in 6-well plastic tissue culture trays (Corning, Corning, NY). Once removed, each seed coat was flattened onto opaque white plastic using transparent tape (Scotch packaging tape, 3M), and digitally photographed. Images of seed coats were analyzed using ImageJ software (NIH, Bethesda, MD) to obtain surface area (Reinking, 2007). The identity of each individual almond was maintained for each measurement so that trends between physical parameters could be observed.

2.2.2. Preliminary data analysis and modeling

A multivariate linear model was created with JMP software (version 10, SAS Institute Inc., Cary, NC) using a stepwise method to predict measured imbibed surface area on the 344 almonds made up of Nonpareil, Monterey, and Butte–Padre almonds from the 2009 crop. Thirty-three possible model effects were used in