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Megan Fisklements, Diane M. Barrett

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Title:
Kinetics of Almond Skin Separation as a Function of Blanching Time and Temperature

Author names and affiliations:
Megan Fisklements\textsuperscript{a} and Diane M. Barrett\textsuperscript{b}
Department of Food Science and Technology, University of California, One Shields Avenue, Davis, CA 95616-8598, USA
\textsuperscript{a}maclements@ucdavis.edu
\textsuperscript{b}Corresponding author. dmbarrett@ucdavis.edu

Abstract:
This study was undertaken to better characterize the process of almond seed coat (a.k.a. skin) separation via hot water submersion, a process often referred to as ‘blanching’. The degree of skin separation on individual almonds was measured after varying treatment times and temperatures, and modeled empirically. At all tested temperatures (100\,\textdegree{}C to 70\,\textdegree{}C), separation progressed along a sigmoidal logistic curve. Applying the concepts of microbial lethality kinetics to seed coat separation, $D_{\text{separation}}$ values were 24 seconds at 90\,\textdegree{}C (194\,\textdegree{}F), 118 seconds at 80\,\textdegree{}C (176\,\textdegree{}F), and 443 seconds at 70\,\textdegree{}C (158\,\textdegree{}F). From these, the $z_{\text{separation}}$ value between 70\,\textdegree{}C and 90\,\textdegree{}C was 15.85\,\textdegree{}C degrees. The skin separation rate decreased quickly below 90\,\textdegree{}C (194\,\textdegree{}F). By comparing the rate of seed coat separation, almond varieties, as well as growing, harvesting, and processing conditions could be quantitatively evaluated for their impact on skin separation.

Keywords:
Almonds, skin, kinetics, surface area, D value, z value.

Highlights:
- Kinetics of skin separation at all tested temperatures were logistic and sigmoidal.
• Skin separation rates at 100°C and 90°C (212-194°F) were not significantly different.
• The rate of separation decreased quickly below 90°C (194°F).
• $D_{sep}$ and $z_{sep}$ values were more temperature-sensitive than *Salmonella* Enteritidis PT 30.
1. Introduction

California produced nearly 1.7 billion pounds of almonds in 2010, earning nearly $2.7 billion (Almond Board of California, 2011). Many of these were blanched (seed coat removed using hot water) for use whole, and as slices, dices, slivers, and almond flour (Harris, Uesugi et al. 2012). Despite the prevalence of this postharvest treatment, the optimal conditions of the blanching process are poorly characterized. The general protocol for almond blanching includes exposing the almond kernels to 85-100°C water for 2-5 minutes, and then peeling off the skins (Almond Board of California, 2009). Some almond cultivars have been shown to blanch more easily than others (Lampinen, 2002). In consulting with growers and processors, some harvest and postharvest processes are suspected of affecting skin adherence and ease of blanching. These include orchard growing temperatures and watering schedules, almond maturity at harvest, drying method, and stockpiling and pasteurization conditions. Despite the industry perception that some or all of these processes affect the ease of blanching, there is no information in the published literature pertaining to tailoring the blanching protocol to compensate for these factors. Over-blanching can lead to deleterious texture, flavor, nutrient, and color changes, while under-blanching fails to remove enough skin, necessitating costly reprocessing.

Understanding the kinetics of how almond skin separates from the kernel during blanch-processing can help optimize the process to save energy and lower production costs. Blanch-processing can also be used as a model system for exploring and quantifying unintentional seed coat separation, which grades as a defect according to USDA standards.

This study examines the effects of water temperature and duration of exposure on almond skin adherence in order to uncover the kinetics of the almond seed coat separation process. Quantification of the skin separation response can also be used as a more precise method of evaluating the effect of various pre-, harvest and postharvest treatments on almond skin adherence.
1.1 Seed Coat Development

As shown in Figure 1, the seed coat develops from the inner and outer integuments of the ovule (OI and II, respectively). These are maternal tissues that surround the nucellus and enclosed female gametophyte. An inner cell layer, thought to be endosperm (marked En), often adheres to the seed coat. If it is the endosperm, it is a triploid nutrient tissue that resulted from double fertilization; the other fertilization event produced the embryo. In genetic terms, the endosperm is neither maternal nor embryonic (Hawker and Buttrose, 1980). The peeled almond nut is almost entirely embryonic cotyledon tissue (Co), with only a small embryonic axis to which the colyledons are attached; the most superficial cell layer of the peeled almond is the cotyledon epidermis (CE).

During development, nutrients pass from the maternal tissue to the embryo through vascular bundles (VB) within the seed coat (Sarfatti, 1960). There is no direct vascular connection between the embryo and maternally derived tissue such as the seed coat (Pascual-Albero et al., 1998). The seed coat tissue begins to degenerate and its innermost cells collapse around 14-16 weeks after bloom, and it is dried out by 28 weeks (Hawker and Buttrose, 1980). Hull-split generally occurs 30-35 weeks after bloom, depending on the heat exposure experienced by the tree (Hawker and Buttrose, 1980; Kester, 1996). In Northern California, bloom usually occurs in mid to late February and hull split occurs between late August and early September.

The mature seed coat is comprised of 14.30% fat, 3.66% soluble sugars, and 10.50% protein, on a dry weight basis. It is high in pectin, while gum and mucilage content is only 0.23% (Saura-Calixto et al., 1983).

At almond maturity, the microscopic residual monolayer of endosperm cells is firmly attached to the nucellar remnant and integuments, together making up the seed coat or “skin” of the almond kernel (Kester, 1996; Mandalari et al., 2010). The maternal tissue, triploid nutrient tissue, and embryonic tissues fit tightly together.

1.2 Current Understanding of Seed Coat Separation

There is little published information on the mechanism of seed coat separation in almonds. It is known that the cleavage point of tissues during seed coat separation (Figure 1, arrow) is always located between the cotyledon epidermis and a persistent
monolayer of cells that are considered to originate from the endosperm (Mandalari et al., 2010). The maternal tissue and residual nutrient tissues separate from the embryonic tissue. This location of separation is consistently observed, regardless of whether thermal or non-thermal methods (successive liquid nitrogen dips) are used to separate the seed coat, as shown by Mandalari, et al. (2010). In other words, the location of seed coat separation is not an artifact of heat exposure.

Beyond the specificity of the tissue cleavage location and its independence from heat, nothing has been published about why seed coats separate from the cotyledons at this boundary, the mechanism by which the separation progresses, or how temperature and duration of submersion in hot water affect the rate of seed coat separation. The only clues to these lingering questions are case studies of circumstances where seed coat separation has been observed.

Seed coat separation has been observed in cases of over-drying in batch dryers, especially in almonds close to the heat-source at the bottom of bin-driers (time and temperature conditions unspecified). Brittleness of the seed coat was seen in conjunction with brittleness of the nutmeat itself (Thompson, 1996).

Paulsen and Brusewitz (1976) determined that in peanuts, seed coats have a smaller coefficient of thermal expansion than do the skinless peanut kernel, and therefore peanut seed coats separate as peanut kernels expand faster than the seed coats. In contrast, our preliminary experiments on almond seed coat separation using hot water indicate that almond skins expand faster than kernels in this experimental system; however, this was examined more closely as part of the scope of this research.

Seed coat separation was strikingly more prevalent in the 2008 harvest crop, compared to previous years. This trend was reportedly seen across the entire California growing region (personal communication, Almond Board of California), and caused speculation regarding the effect of cultivation and processing variations such as growing temperatures, watering sources and schedules, almond maturity at harvest, and the use of circulating hot air driers on seed coat adhesion.

This project explored the kinetics of almond seed coat separation as a function of hot water treatment duration and temperature. Development of an empirical model of almond skin separation in response to these variables will facilitate optimization of the blanch-
processing, allowing for measurement and characterization of the seed coat separation process.

2. Methods and Materials

2.1 Raw materials

Almonds used in kinetics modeling experiments were harvested over the 2009-2011 seasons from almond orchards maintained by the UC Davis Department of Plant Sciences. These almonds were harvested at commercial maturity and hulled before storage in plastic bags at room temperature, out of the sunlight, until use. Almonds used in all experiments were the Nonpareil variety. Individual almonds exhibiting any USDA graded defects were excluded from study.

2.2 Hot Water Treatments

Samples comprised of five almonds each were placed in preheated stainless steel quarter inch mesh baskets. Baskets were approximately 10 cm in diameter so that when submerged below the surface of the circulating deionized water bath (Jubalo 20B, Seelbach, Germany), almonds could move freely within them. Kernels were held at 70, 80, 90, or 100°C, as determined with an immersion thermostat (Lauda Ecoline E100, Lauda-Königshofen, Germany). At each experimental temperature, 5 almonds per time-point were submerged in hot water and then analyzed. Sixteen time-points between 120 and 540 seconds were tested at 70°C, nine time-points between 45 and 300 seconds were tested at 80°C, fifteen 90°C durations were tested between 2.5 and 105 seconds, and fourteen times between 2.5 to 65 seconds were tested at 100°C. Three to four replicate runs were performed at each temperature, for a total of over a hundred almonds per treatment temperature.

After treatment, almonds were cooled for a few seconds in room temperature water to render them safe to handle before seed coat separation was quantified.
2.3 Quantification of Seed Coat

In order to remove seed coats that had been loosened during treatment, groups of five almonds were manually rolled back and forth in a soft silicone tube (Zak Designs, Airway Heights, WA) three times, for a distance of 25 cm each way, using approximately 3.5 kg of applied pressure. This rolling procedure did not remove well-adhered seed coats in unimmersed controls.

Automation of this process was attempted by inserting the soft silicone tube into a TA.XT2 texture analyzer (Texture Technologies, Scarsdale, NY) fitted with a horizontal Lexan sled fixture rig (TA-265). However, the sled was too short to steadily accommodate enough weight to shear off loose almond seed coats. A custom rig was commissioned from the UC Davis machine shop, but application of the weight required to shear off the almond seed coats caused load errors in the Texture Analyzer. From what data could be gathered, it appeared that the change in horizontal friction as the almond seed coats were sheared off was slight compared to the variation introduced as the non-spherical almonds erratically rolled within the rig. Attempts to automate the seed coat separation were abandoned once results with manual rolling were shown to be repeatable between researchers.

After rolling, seed coats that had visibly loosened, but had not yet fallen away from the kernel were carefully removed with a scalpel. After removing any loosened seed coat, almonds were placed into 6-well or 12-well plastic cell culture trays (Corning, Corning, NY). Wells were filled with deionized water, and allowed to sit for 24 hours at 4°C. Following rehydration, residual seed coats were manually peeled from each almond kernel and adhered onto a sheet of opaque white plastic using transparent tape (Scotch packaging tape, 3M). Seed coats were digitally photographed and images were analyzed using ImageJ software (NIH, Bethesda, MD). A pixel count for each seed coat was converted to surface area using a ruler captured within each image for scale.

During imbibition, almonds take up water. Preliminary studies determined empirically that by 24 hours, soaking almonds equilibrate in deionized water, and their mass stabilizes. Weights of kernels soaked more than 24 hours were not significantly different from those at any time-points afterwards, by Tukey-Kramer means comparison test; therefore, this was chosen as the standard imbibition time.
After submerging in hot water, rolling, and rehydration, measurements of length, width, and mass were taken from fully imbibed almonds. Selection of these parameters was based on preliminary experiments. Surface area modeling performed previously found that measured surface area correlated more closely with the dimensions of rehydrated almonds than with the dimensions of dry almonds (Clements, 2013).

Using an empirical model described previously (Clements, 2013), the surface area of each imbibed almond could be calculated ($r^2 = 0.74$) based on its length, width, and mass after rehydration, using equation 1:

Equation 1: Total Surface Area = $-300.67 + 15.36 \times \text{length} + 34.12 \times \text{width} + 99.11 \times \text{imbibed mass}$

Note: the first term in Equation 1 is a constant, and includes a varietal factor, which is different for different almond varieties. The value of -300.67 corresponds to the Nonpareil variety, and only Nonpareils were used in this study. For values to use while modeling the surface areas of other varieties, refer to Clements (2012).

The fraction of each seed coat that was missing from individual almonds following hot water treatment was quantified using Equation 2 (Clements, 2013):

Equation 2: Percent of seed coat missing = $100 \times (\text{total surface area} – \text{remaining seed coat})/\text{total surface area}$

Using the total surface area estimate and the measured surface area of any remaining portion of seed coat, a quantitative percent of seed coat missing was calculated.

2.4 Modeling

In order to ascertain the rate of the seed coat separation during hot water treatment, non-linear two-parameter logistic regression was performed using JMP statistical software (SAS Institute Inc., Cary, NC). The Analytic Gauss-Newton method was used to iteratively fit each model to the data, with an alpha of 0.05, and a convergence criterion of 0.00001 (SAS Institute Inc., 2010). Duration of hot water submersion was used as the independent variable, and the response variable was the calculated fraction of seed coat missing from each almond. In order to preserve as much precision as possible during the modeling process, raw data from experimental replicates of each temperature were not
pooled, but were instead modeled separately as independent runs, and the modeled reaction rates were subsequently compared. The rates of seed coat separation at each temperature were compared using ANOVA and the Tukey-Kramer HSD test.

2.5 $D_{\text{sep}}$ and $Z_{\text{sep}}$ Value Calculations

The decimal reduction time ($D$ value) used in microbiology describes the treatment duration that causes 90% microbial inactivation. In the same way, the authors suggest $D_{\text{sep}}$ as a useful description for the hot water immersion time required to separate 90% of the seed coat. Likewise the $z$-value traditionally describes the temperature change required to alter the microbial inactivation $D$ value by a factor of 10. This principle may be applied to seed coat separation in the form of a $z_{\text{sep}}$-value denoting the temperature change that alters the $D_{\text{sep}}$ by a factor of 10. A $D_{\text{sep}}$ was calculated for each temperature based on the results of skin separation profile kinetics modeling. The $z$-value was calculated as the inverse slope of the log $D_{\text{sep}}$ values, plotted against their corresponding temperatures.

While tracking and predicting the attainment of 90% seed coat removal is not specifically of great significance in industrial skin removal using hot water, it can serve as a proxy for complete seed coat separation, and is calculated in a section of the model that is more precise than at the 100% end-point. Using these $D_{\text{sep}}$ values and the $z_{\text{sep}}$ value, the $D_{\text{sep}}$ value at any temperature between 70°C and 90°C can be calculated. Calculating the time and temperature conditions necessary for seed coat separation at different temperatures could better inform energy usage and product quality decisions about raising or lowering water temperatures in processing facilities in order to achieve or prevent seed coat separation.

3. Results and Discussion

Immediately after hot water treatment, almond seed coats appeared larger than the kernels within them. After soaking overnight, almond kernels had swollen along with their seed coats, and fit tightly within their seed coats again (Figure 2).
The opposite trend was observed by Paulsen and Brusewitz (1976) in peanuts, who determined that peanut seed coats have a smaller coefficient of thermal expansion than do the skinless peanut kernels. However, their experiments were performed at constant moisture levels of 2.4%-29% moisture (dry basis) without immersing them, and therefore are not analogous to almonds with seed coats removed through submersion in water.

3.1 Seed Coat Separation Profiles and Modeling

At each temperature, the mean fraction of separated seed coat increased with duration of hot water immersion along a logistic sigmoidal curve. Figure 3 shows the skin separation profiles of almonds submerged in 70°, 80°, 90°, and 100°C water, averaged over all replicate runs, with error bars showing standard error of the mean at each time-point. Determining the surface temperature of an almond is challenging since the introduction of a thermocouple probe at the surface would be foiled by the same seed coat separation being measured here. Harris et al. faced the same challenge, and resourcefully estimated the come-up time of an entire almond to be 30 seconds, using an almond-shaped piece of aluminum with a built-in thermocouple, and back-calculating heat transfer using both the thermal conductivity of aluminum and of almonds (by composition) (Harris et al. 2012). However, after 30 seconds, much of the almond seed coat has already separated from the kernel when treated at 100°, 90°, and 80°C, so waiting until the almond temperature has stabilized is not an option when monitoring the progress of the seed coat separation. The dynamic temperature of the almond surface during the first portion of hot water immersion could likely be partially responsible for the initial lag in skin separation seen in the sigmoidal curve of the seed coat separation profiles in Figure 3. Water migration and tissue hydration is doubtless also a factor. Given that all almond samples were stored at a uniform ambient temperature of 25°C prior to experiments, and that the process of seed coat separation only involves the first ~60um of the almond, it is assumed for the purposes of this work that water temperature may be used as a practical proxy for almond surface temperature until a superior method can be found.

Skin separation progressed more slowly at lower temperatures. All seed coats were separated after about 50 seconds of submersion at 90°C and 100°C, and after 3.5-4
minutes at 80°C, whereas submersion at 70°C required 7-9 minutes to completely remove seed coats.

Similar indications of this trend were observed by Harris et al. (2012), who noted that after 4 minutes of heating in a 60 or 70°C water bath, only a few almonds exhibited skin coat separation while complete seed coat separation occurred in less than 4 minutes at 88°C. However, these authors observed only minimal obvious seed coat separation after 4 minutes at 80°C (Harris et al., 2012), while research reported here saw significant seed coat separation after this degree of thermal treatment (Figure 3). This may be accounted for by the different almond varieties being tested. Harris et al. (2012) worked with Carmel almonds, while experiments reported here were performed on Nonpareil almonds. Lampinen et al. (2002) compared the ease of seed coat separation in hot water of 18 different almond varieties at 85°C for 3 minutes, and found that Carmel almonds were slightly more resistant to seed coat separation than were Nonpareil almonds.

Once data detailing the extent of almond seed coat separation at each time-point and temperature were collected, it was modeled using non-linear least squares regression. A 2-parameter logistic model was fit to the fraction of seed coat missing from individual almonds within each separate experimental run (Table 1). Three to four replicate hot water submersion experiments were conducted at each temperature of interest, e.g. 70°, 80°, 90° and 100°C. The logistic modeling formula is shown in Equation 3:

Equation 3: \[
\frac{\text{Fraction of seed coat separated}}{\text{100}} = \frac{1}{1 + e^{-\text{reaction rate}}} 
\]

Modeled skin separation reaction rates (k values) and pre-exponential factors (a values) for individual runs at each temperature are shown in Table 1. The average seed coat separation rate at each temperature can be found in Table 2.

Seed coat separation rates ranged from 0.171-0.384 sec\(^{-1}\) at 100°C, from 0.125-0.271 sec\(^{-1}\) at 90°C, 0.039-0.087 sec\(^{-1}\) at 80°C and 0.011-0.016 sec\(^{-1}\) at 70°C. At each time and temperature combination, the five almonds evaluated typically did not respond to hot water immersion in a uniform fashion. For example, it was common for complete seed coat separation to occur in one or more of the almonds, while others had incomplete separation. This variation in the response of individual almonds is likely due to exposure to many small differences in growing conditions, slight maturity differences or variability in postharvest stress exposure. The range in responses between individual almonds within
each treatment time and temperature resulted in somewhat elevated root mean square errors, as shown in Table 1. The root mean square error describes the spread between seed coat separation of individual almonds and the modeled seed coat separation (SAS Institute Inc., 2010). However, mean seed coat separation values and modeled values corresponded closely, as shown in Figure 3. Representative skin separation profiles (Figure 3) include closed symbols denoting the degree of empirical seed coat separation (mean of five or more almonds), while open symbols show modeled values. While the rate of skin separation slowed at temperatures lower than 90°C, profiles at all temperatures were logistic and sigmoidal. During assay development, a 90°C run was performed that contained only two measured time-points capturing almonds at intermediate degrees of seed coat separation; at the other tested time points, almonds exhibited no or total seed coat separation (data not shown). As a result of this dearth of data, the standard error was quite high. However, the data did accurately capture the beginning and ending time-points of seed coat separation; therefore, the seed coat separation rate was within range of subsequent 90°C replicates. This underscored the reliance of the model’s precision on measuring seed coat separation at an adequate number of time-points in the period of time when the seed coat is changing quickly, after separation has begun to appear, and before it is complete. This also highlights the model’s robustness in calculating skin separation rate, so long as data is collected at time-points closely bracketing the window for the seed coat separation. The average skin separation rates \((k)\) increased with temperature from 0.013 \(\text{sec}^{-1}\) at 70°C to 0.254 \(\text{sec}^{-1}\) at 100°C. The 0.206 \(\text{sec}^{-1}\) rate of separation at 90°C was not significantly different from the rate of separation at 100°C according to the Tukey-Kramer HSD test (Table 2). Skin separation at 80°C progressed at 0.066 \(\text{sec}^{-1}\), 3.8 times slower than at 100°C, while separation at 70°C progressed 19.3 times slower than 100°C. The \(k\) and \(a\) values associated with each treatment temperature in Table 2 can be used in Equation 3 to predict the percent of seed coat separation expected after various treatment times at temperatures between 70 and 100°C. This can be used to anticipate the effect of lowering or raising treatment temperatures on seed coat separation, and to predict the required duration of hot water exposure that will remove the same fraction of seed coat at an altered treatment temperature.
The decimal reduction time ($D_{sep}$ value) of hot water treatment required to remove 90% of the seed coat ranged from 30 seconds at 100°C to 443 seconds at 70°C. The $z_{sep}$-value for decimal reduction times between 70°C and 90°C is 18.48 °C degrees. Using these $D_{sep}$ values and $z_{sep}$ value, the $D_{sep}$ value at any temperature between 70°C and 90°C can be calculated.

As shown in Figure 4, linear regression of log10 skin separation rates versus treatment temperature in the range of 70°C through 90°C was strong ($r^2=0.931$), with no evidence of departure from linearity using Lack of Fit analysis (p=0.718). However, when skin separation rates at 100°C were included, a significant lack of fit was observed (p<0.0001). Seed coat separation rate only falls linearly with decreasing temperature under around 90°C. This may imply a threshold temperature around 90°C, below which skin separation rate lowers with lower temperatures, and above which, separation rate is not strongly affected by temperature. Testing this hypothesis would entail experimentation at additional temperatures to pinpoint the threshold temperature, and to find where this trend breaks down. The plateau of seed coat separation rate change could also be due, in part, to the lag between water bath temperature and almond surface temperature.

Harris et al. observed $D$ values for *Salmonella* enteritidis PT 30 of 156, 72, 45, and 23.4 seconds at 60, 70, 80, and 88°C, respectively, and a $z$ value of 35°C degrees between 60°C and 88°C (Harris et al., 2012). These $D$ values for *Salmonella* are higher than the $D_{sep}$ values for seed coat separation, meaning that at temperatures ranging from 70°C-100°C, almond seed coats separate faster than *Salmonella* is killed. For example, at 80°C, a 4-log *Salmonella* kill would take 180 seconds, meanwhile 99% of the seed coat would have separated after 156 seconds.

Interestingly, the *Salmonella* inactivation $z$ value observed by Harris et al. is much higher than the seed coat separation $z_{sep}$ value calculated in this study, meaning that as treatment temperature falls, the rate of skin separation slows more than the rate of *Salmonella* killing. At 70°C, a 4-log *Salmonella* kill requires 288 seconds. After this treatment, only 54% of almond seed coat will be separated. Based on this trend, it’s possible that at a low enough temperature, significant seed coat separation would not yet have occurred before pasteurization had been accomplished. Based on extrapolations from $D$ and $D_{sep}$ values
and z and $z_{\text{sep}}$ values, this may occur around 60°C, but further experiments would be needed to determine whether the observed temperature-dependent trend in seed coat separation rates holds at temperatures below 70°C.

4. Conclusions

Mean seed coat separation in response to duration of hot water treatment progressed along a sigmoidal logistic curve. In a typical logistic pattern, the slowing reaction rate at the high end of the curve often corresponds to saturation conditions, which slow the growth of the dependent variable. In the case of almond skin separation, it was observed that the last part of seed coat to separate was always the darkly pigmented chalazal spot at the broad end of the almond. This region of the seed coat appeared to adhere more strongly to the underlying nutmeat, and seemed to anchor the skin immediately surrounding it, slowing the rate of seed coat separation for the final 10-20% of the seed coat. This stronger adhesion is consistent with its essential function in nutrient flow during almond development (Sarfatti, 1960).

$D_{\text{sep}}$ values representing 90% seed coat separation were calculated as 35 seconds at 90°C, 120 seconds at 80°C, and 443 seconds at 70°C. From these, a $z_{\text{sep}}$ value for decimal reduction times between 70°C and 90°C was calculated at 18.48 C degrees. These numbers can be used to interpolate the minimum necessary duration of treatment at any temperature between 70-90°C. Such information could better inform assessments of the time and energy input consequences of lowering water temperature on pilot- and commercial scales. Comparison between microbial inactivation D and z values reported for Salmonella Enteritidis PT 30 (Harris et al., 2012) and $D_{\text{sep}}$ and $z_{\text{sep}}$ values observed in this study indicate that Salmonella is more vulnerable to destruction than almond seed coat adherence is at lower water temperatures. This indicates the possibility of low-temperature long-time pasteurization at temperatures below the range examined in this study.

Using this new method, almond processing conditions can be optimized to reduce the chances of accidental seed coat separation, or to more efficiently achieve it. Quantifying the rate of seed coat separation could also potentially be used to compare different
almond varieties, as well as evaluating growing, harvesting, and processing conditions for their effect on skin separation.

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6. Works Cited


List of Tables

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Table 1. Almond skin separation model parameters of individual experimental run replicates at 70°, 80°, 90°, and 100°C.

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<td>27.94</td>
<td>12.67</td>
<td>116</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.276 c</td>
<td>0.111</td>
<td>302.80</td>
<td>709.50</td>
<td>34</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.384 c</td>
<td>0.056</td>
<td>566.65</td>
<td>532.22</td>
<td>39</td>
<td>0.11</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.184 c</td>
<td>0.035</td>
<td>23.77</td>
<td>14.99</td>
<td>44</td>
<td>0.20</td>
</tr>
</tbody>
</table>

<sup>a</sup> Separation rates followed by different letters were significantly different by the Tukey-Kramer HSD test.
Table 2. Mean skin separation rates based on data from all pooled runs at 70°, 80°, 90°, and 100°C.

<table>
<thead>
<tr>
<th>Water Temp (°C)</th>
<th>Replicates</th>
<th>Separation Rate ($k$, sec$^{-1}$)</th>
<th>Standard Error of $k$</th>
<th>Standard Error of $a$</th>
<th>$D_{sep}$ value (sec)</th>
<th>$z_{sep}$ value (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>70</td>
<td>3</td>
<td>0.013 a$^a$</td>
<td>0.003</td>
<td>37.07</td>
<td>24.15</td>
<td>442.6</td>
</tr>
<tr>
<td>80</td>
<td>4</td>
<td>0.066 a,b</td>
<td>0.020</td>
<td>304.10</td>
<td>261.54</td>
<td>119.6</td>
</tr>
<tr>
<td>90</td>
<td>3</td>
<td>0.206 b,c</td>
<td>0.074</td>
<td>149.84</td>
<td>84.65</td>
<td>35.0</td>
</tr>
<tr>
<td>100</td>
<td>4</td>
<td>0.254 c</td>
<td>0.099</td>
<td>230.29</td>
<td>259.48</td>
<td>30.1</td>
</tr>
</tbody>
</table>

$^a$ Separation rates followed by different letters were significantly different by the Tukey-Kramer HSD test.
Figure 1. Micrograph of a Nonpareil almond seed in cross-section, stained with toluidine blue O, showing the layers that originated from maternal tissue (outer integument, OI; inner integument, II; vascular bundles, VB; nucellus, Nu); from the triploid nutritive tissue (endosperm, En), and from the embryonic tissue (cotyledon epidermis, CE; and underlying cotyledon tissue, Co). Arrow indicates the seed coat layers that dissociate from the embryo during seed coat separation.

Figure 2. A Nonpareil almond immediately after 45 seconds blanching at 100°C (left), next to an almond that underwent identical blanching treatment followed by 24 hours of rehydration (right).

Figure 3. Blanching profiles of Nonpareil almonds at 70°, 80°, 90°, and 100°C, averaged over all replicate runs. Error bars show standard error of the mean.

Figure 4. Blanching profiles at 70°, 80°, 90°, and 100°C modeled based on data from all pooled runs. Model predictions are indicated by open symbols, while average observed values are shown with closed symbols.

Figure 5. Semi-logarithmic graph linearizing the effect of temperature on blanching rate between 70°C and 90°C.
Maternal Tissue
Nutritive Tissue
Embryonic Tissue (Cotyledon)
\[ y = 0.059x - 5.992 \]
\[ R^2 = 0.930 \]
Highlights

- Kinetics of almond blanching at all tested temperatures were logistic and sigmoidal.
- Blanching rates were not significantly different between 100°C and 90°C (212-194°F).
- The rate of blanching decreased quickly below 90°C (194°F).
- Harvest at hull-split then forced hot air drying did not appear to reduce skin adherence.
- Blanching D and z values were more temperature-sensitive than Salmonella Enteritidis PT 30.