Original article

Chemical changes in almonds throughout storage: modeling the effects of common industry practices

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Summary

Further investigations of almond degradation under typical industrial storage conditions from a quantitative perspective are warranted. This study modeled effects of packaging, temperature (TEMP), relative humidity (RH) and roasting on chemical attributes of almonds stored according to common industry practices throughout 16 months. Roasted samples were stored in high-barrier bags (HBB) or polypropylene bags (PPB) at multiple combinations of TEMP and RH. Raw samples were held in unlined cardboard cartons (UC) or PPB under the same conditions. Almonds were assessed bimonthly for oxidation products, free fatty acids, moisture content and water activity. Results indicated roasting almonds improved quality preservation. Models showed HBB (rather than PPB) to provide benefits to stability comparable to reductions in storage TEMP of ~15 to 30 °C. PPB (rather than UC) showed benefits to peroxide formation of similar magnitude. Our data shows HBB to be a superior packaging choice, and UC to associate with the greatest rates of degradation.

Keywords

Almonds, lipid oxidation, mathematical model, packaging materials, shelf life.

Introduction

Almonds have been the largest specialty crop export in the United States (USDA, 2013). During storage, the physical and chemical quality of almonds will degrade and eventually result in consumer rejection (Franklin et al., 2017). Current industry practices include storing raw almonds in unlined cardboard cartons (UC), and roasted almonds either in polypropylene bags (PPB) or high barrier bags (HBB) (ABC, 2015). Numerous temperature (TEMP) and environmental relative humidity (RH) conditions may be implemented during commercial storage.

Due to their high percentage of unsaturated fatty acids, almonds are prone to oxidation (Sathe et al., 2008). Internal factors such as moisture content (MC) of the nut, physical characteristics of the nut, fatty acid composition, antioxidant content and surface area will also affect the rate of oxidation in almonds (Fennema, 1996; Shahidi & John, 2013). RH, O2 content, TEMP, light exposure and packaging materials are all controllable factors that may affect the relative rates of oxidation in stored tree nuts (Mate et al., 1996).

Because almonds are low moisture foods, they are somewhat prone to moisture absorption. Increased MC or water activity (aw) within the nut kernel reduces the overall stability of the tree nut by increasing rates of oxidation (Evranuz, 1993). Textural attributes such as crispness, crunchiness and chewiness are also directly related to the MC, and can be affected by storage RH (King et al., 1983).

Roasting of almonds is also relevant to stability. Roasting of tree nuts is a common thermal process used to create specific flavor notes, darken color and add a more desirable crispy texture (Perren & Escher, 2013). Typically, the MC and aw are reduced while levels of CO2 and product brittleness are increased (Severini et al., 2000). Roasting can cause several
simultaneous changes to the quality of almonds. While the exposure to heat during roasting tends to directly increase rates of lipid oxidation, the process also produces Maillard reaction products with antioxidant properties that slow subsequent lipid oxidation in stored almonds (Severini et al., 2000). Almond kernels have a compartmentalised microstructure that protects against oxidation, and evidence has shown this protective microstructure can be disrupted by roasting (Perren & Escher, 2013). A recent study investigated light roasted and dark roasted almonds and found that although peroxides proliferated at a greater rate in dark roasted almonds, consumer liking was not significantly different between light and dark roasted almonds (Franklin et al., 2017).

Packaging under a N2-atmosphere slows autoxidation when compared with packaging in air (Sanchez-Bel et al., 2011). Cardboard cartons provide no protection against transmission of water vapor or oxygen. PPB limits transmissions of water vapor and oxygen to approximately 8 g m⁻² d⁻¹ and 860 cm² m⁻² d⁻¹, respectively, and HBB limits these to <0.5 g m⁻² d⁻¹ and <1 cm² m⁻² d⁻¹. A recent study specifically compared the stability of peanuts stored in PPB with those stored in HBB and found the HBB to better preserve the peanuts by measurements of peroxide value (PV), free fatty acid values (FFA), α-tocopherol losses, mold increase and sensory detection of cardboard off-flavors (Martín et al., 2016). Another recent study compared storage of roasted almonds in HBB vs. PPB in regards to consumer assessment and found HBB to substantially mitigate the degradation of acceptability (Cheely et al., 2018).

The impact of extrinsic and intrinsic factors involved during storage on the quality of almonds requires further investigation and quantitation. This study aimed to measure the classical primary and secondary lipid oxidation products/markers (i.e., 1º – PV, FFA value, conjugated dienes value; 2º – 2-thiobarbituric acid reactive substances) of almond degradation, as affected by roasting, packaging and storage conditions. The objective was to quantify the effects of storage variables and to build mathematical models for predicting the storage life of almonds to assist the almond industry in redefining recommendations of storage practices.

Materials and methods

Study design

The effects of environmental storage conditions on raw and roasted almond quality characteristics were investigated with an incomplete factorial design. The combinations of factors were chosen in consultation with the Almond Board of California to be truly representative of storage strategies currently practiced by industry members. Different permutations of the possible factors produced 25 unique samples for assessment (Fig. 1). Raw almonds were divided into fourteen unique sample groups according to combinations of TEMP (n = 3), RH levels (n = 3) and packaging materials (n = 2). Two packaging materials were selected to compare performance of raw almonds stored in current industry packaging strategies (UC) against more robust packaging strategies (sealed N2-flushed PPB).

Roasted almonds were divided into eleven unique sample groups according to predetermined combinations of TEMP (n = 3), RH levels (n = 3), and packaging materials (n = 2). Two packaging materials were selected to compare performance of roasted almonds stored in current industry packaging strategies (sealed N2-flushed HBB) against less robust packaging strategies (sealed N2-flushed PPB). Sealed N2-flushed PPB were used for both raw and roasted almonds to compare the performance of raw and roasted almonds packaged in identical packaging strategies.

In our laboratory, raw and roasted almond samples were evaluated bimonthly until the conclusion of 16 months of storage or until “sensory rejection failure” was noted by a consumer panel. Sensory rejection criteria have been reported for the raw and roasted almonds by Pleasance et al. (2018) and Cheely et al. (2018), respectively. Sensory failure occurred for a sample once >25% of the panelists on a consumer panel (n = 100–120) “rejected” it (answering “No” to the question of, “If you had purchased this product, would you eat it?”). Chemical assessments began at day 0 of storage and concluded with measurements at the point of sensory failure, or after 16 months, whichever occurred first.

Replicate treatments described for the chemical assessments refer to acquisition of data from a single package. If conducting multiple assessments on the same day, a single storage bag could be used to provide samples for multiple assessments. Once a package was removed from incubation for sample collection, it was discarded at the end of the day.

Sample handling and packaging

Almonds were stored in conditions truly representative of common industry practices. Raw almonds were kept in Uline S-17960 PPB (100 μm thickness; Uline, Waukegon, IL, USA) or U-line S-15138 UC. The PPB material had a reported water vapor transmission rate (WVTR) of 8 g m⁻² d⁻¹ and an oxygen transmission rate (OTR) of 860 cm³ m⁻² d⁻¹. The UC provided no protection from atmospheric conditions. Thirty PPB per treatment were vacuumed, flushed with food-grade N2, and sealed with an initial O2 level below 0.5% using a Henkelman 600 vacuum packaging system (Henkelman B.V., The Netherlands). Each sealed N2-
flushed PPB had been filled with 300 g ± 5 g of almond kernels. Twelve UC per treatment were filled with 900 g ± 5 g of raw almonds. Roasted almonds were kept in Uline S-17960 PPB (100 µm) or ABC metallised film laminate HBB (100 µm PET, 100 µm Al, 75 µm PE thickness; StandUpPouches, Avon, OH, USA). The PPB material was the same as that used for raw almonds. The laminate material (PET/Al/PE) had a WVTR < 0.5 g m⁻² d⁻¹ and OTR < 1 cm³ m⁻² d⁻¹. Thirty PPB and HBB per treatment were vacuumed, flushed with food-grade N₂, and sealed with the initial O₂ level < 0.5% using the vacuum packager (Henkelman B.V., 's-Hertogenbosch, The Netherlands). Each sealed N₂-flushed PPB and HBB was filled with 300 g ± 5 g of almond kernels.

For storage, Hotpack model 434304 (SP Industries, Warminster, PA, USA) environmental chambers were used at 35 °C/65% RH, 35 °C/50% RH and 25 °C/65% RH. To achieve 25 °C/50% RH, 15 °C/65% RH and 15 °C/50% RH conditions, Hotpack model 435314 environmental chambers were employed. To maintain adherence to conditions representative of common industry practices, all samples stored in HBB and/or at 4 °C were stored at uncontrolled RH. HBB samples stored at 35 °C were stored in a Thelco Precision Scientific Model 6 Incubator (ThermoFisher Scientific Inc., Waltham, MA, USA). HBB samples stored at 25 °C and 15 °C were stored in Thermo Scientific Incubators (ThermoFisher Scientific Inc.). All samples stored at 4 °C were stored in a walk-in cooler (Nor-Lake, Inc., Hudson, WI, USA). Chambers were monitored continuously using an Extech RHT-10 TEMP/RH probe (Extech Instruments Corporation, Nashua, NH, USA) to ensure accuracy of storage conditions. Once a random package was removed from an environmental chamber, the almonds were assessed, and the package with any leftover sample was then discarded. In other words, all assessments were conducted on samples that had received uninterrupted storage from day 0 to the point of analysis with a constant mass in the bag and no change in the sample's headspace.

Raw almond samples
Raw almonds (*Prunus dulcis*) were ‘Nonpareil’. The almonds were collected from a composite lot of commercial almonds that had been harvested from twelve different orchards in the Central Valley of California. Almond samples were sized, graded and then pasteurised by propylene oxide using a standard industry protocol at the Blue Diamond Growers’ Almond Processing Plant (Sacramento, CA, USA). All raw almonds were pooled and mixed in a single composite sample prior to implementing the storage study. These almond samples are designated as “raw” throughout the study.

Roasted almond samples
‘Nonpareil’, supreme-grade, raw almond kernels with brown skins were processed and pasteurised as described above. Almonds were then dry-roasted for 68 min at 122 °C at the Blue Diamond Growers’
Almond Processing Plant to achieve a light roast. All roasted almonds were pooled and mixed in a single composite sample prior to implementing the storage study. These samples are designated as “roasted” throughout the study.

**Lipid extraction**

Whole almond kernels were placed in a Carver 2.25” ID stainless steel test cylinder and pellet mold, and cold-pressed in a #3912 Carver hydraulic press (Carver, Inc, Wabash, IN, USA) to extract the cold-pressed oil (CPO). The CPO was transferred to 30-mL amber screw-cap vials (Fisher Scientific, Suwanee, GA, USA), flushed with N₂, and stored in a dark, 4 °C refrigerator overnight until analyses were completed the next day.

** Grinding**

Forty-five grams of whole almond kernels were ground using a Cuisinart DCG-12BC (Cuisinart, East Windsor, NJ, USA) mill for 10 s with vigorous shaking. Samples were sorted and passed through a 16-mesh Tyler standard screen (W.S. Tyler Industry Group, Mentor, OH, USA). This powder is referred to as ground almond powder.

**Peroxide value (PV) determinations of oils and fats**

Peroxide values were determined using the CPO by a modified procedure according to AOAC Method 965.33 (AOAC International, Gaithersburg, MD, USA). Samples were evaluated in triplicate, using 5.00 g sample for each analysis, and reported as a PV (meq. active O₂ (peroxide)/kg oil). PVs were calculated using the following eqn (1):

\[
PV = \frac{(S \times N \times 1000)}{(\text{mass}(g))}
\]

where, \(S\) is the volume in mL of \(\text{Na}_2\text{S}_2\text{O}_3\) consumed; \(N\) is the normality of the \(\text{Na}_2\text{S}_2\text{O}_3\) solution; and mass represents the mass of the test oil sample evaluated.

**Free fatty acid (FFA) values**

Free fatty acids were determined using the CPO by a modified procedure according to AOCS Official Method Ca 5a-40 (AOCS, Urbana, IL, USA). Samples were evaluated in triplicate and reported as a FFA value (mg KOH required to neutralise 1 g of sample), calculated according to the following eqn (2):

\[
\text{FFA} = \frac{((\text{mL KOH} \times M \times 28.2)/ (\text{Mass}(g))) \times 1.99}{(\text{mass}(g))}
\]

where, \(M\) is the molarity of the KOH consumed; and mass represents the mass of the oil evaluated.

**2-Thiobarbituric acid reactive substances (TBARS) direct method**

2-Thiobarbituric acid reactive substances (TBARS) values were determined using the CPO by a modified procedure according to AOCS Official Method Cd 19-90 (AOCS). Samples (1 g oil for each assessment) were evaluated in triplicate and reported as a TBARS value (reaction equivalent of 1 mg test sample per 1 mL volume with 2-thiobarbituric acid), calculated using the following eqn (3):

\[
\text{TBARS} = \frac{(10 \times (A - B))}{M}
\]

where, \(A\) is the absorbance of the test solution measured at 532 nm; \(B\) is the absorbance of the reagent blank; and \(M\) is the mass (mg) of the test sample portion.

**Conjugated diene (CD) values**

Conjugated dienes (CDs) were determined using the CPO by the procedure according to IUPAC Official Method 2.505 (IUPAC, Research Triangle Park, NC, USA). Samples (1 g oil for each assessment) were evaluated in triplicate and reported as a CD value. CD values were calculated using the following eqn (4):

\[
\text{CD} = \frac{(A_k)}{((C_L \times \ell))}
\]

where, \(A_k\) is the absorbance of the test solution measured at either 233 or 268 nm; \(C_L\) is the concentration of the lipid in g/100 mL; and \(\ell\) is the path length of the quartz cuvette (cm).

**Moisture content (MC) determination**

The MC was determined from ground almond powder by weighing ground almond samples (1 g powder for each assessment) and heating in a forced-air convection oven at 105 °C until a constant weight was achieved. Samples were evaluated in triplicate and reported as a mean ± SD MC, using the following eqn (5):

\[
\text{MC(\%)} = 100 \times \frac{\text{Sample mass after drying (g) \times 100}}{\text{Sample mass before drying(g)}}
\]

**Water activity (\(a_w\)) determination**

The \(a_w\) was determined from ground almond powder by loading 2 g (±0.1 g) into a calibrated Aqua Lab...
CX-2 water activity meter (Pullman, WA, USA). Samples were evaluated in triplicate and reported as a mean ± SD $a_w$ value.

Statistical analysis

For all chemical measures, changes in assessed values were plotted for each sample (i.e., combination of roasting classification, package type, TEMP and RH; assessed in triplicate for each data point) over time (with months being the independent variable). From these plots, SAS Statistical Software (SAS version 9.4, SAS Institute, Inc., Cary, NC, USA) was utilised to identify the slope of the line of the best fit of the curve through the origin. The slopes of these curves represent the rate of modeled proliferation of the assessed measure per month. Hereafter, these slopes are referred to as “proliferation rates”.

The proliferation rates were then treated as dependent variables by subsequent predictive multivariable modeling procedures. Roasting, storage and packaging factors were considered for the development of models predicting the proliferation rates. Because it was not controlled for all samples, RH was not included for consideration as an independent variable in these models. Due to the unbalanced nature of the study design, the procedures for the development of mathematical models were performed on three not mutually exclusively subdivisions of the data: (i) Samples in PPB; (ii) Raw Samples; and (iii) Roasted Samples. In all cases, the multivariable models were developed using the “Best Subsets” procedure by SAS software, with selection of variables for inclusion made according to greatest adjusted $R^2$ value. Models with no significant factors ($\alpha = 0.05$) were not reported.

Results and discussion

Proliferation rates for chemically assessed quality parameters

The modeled monthly proliferation rates (slopes of best fit lines through the curve throughout 16 months of bimonthly assessment) for all assessed measures of quality are reported in Table 1.

For PV, for which the growth over time indicates the occurrence of primary lipid oxidation, the modeled proliferation rates suggest several clear trends. The samples in HBB show lower rates of peroxide formation than those in PPB, and the samples in PPB outperform (i.e., exhibit lower rates of formation than) those in UC. In the raw samples, it is worth noting that the three samples in PPB stored at relatively extreme conditions (i.e., 35°C/65% RH, 35°C/50% RH, and 25°C/65% RH) all showed peroxide formation rates comparable to their counterparts stored in UC. However, in more favourable conditions, the samples in PPB demonstrated markedly lower formation of peroxides, while those in UC remained comparably high. This suggests that, regarding peroxide formation, and providing a moderately favorable storage TEMP and RH may be necessary for PPB to exhibit substantial benefits vs. UC. In a comparison of PPB and HBB in roasted samples, the PPB samples demonstrated PV proliferation rates two to three times greater than those stored at equivalent temperatures in HBB. As would be expected, the lowest rate of proliferation of peroxides occurred in samples stored in HBB at 4°C.

For CD, another positive indicator of primary lipid oxidation, the modeled proliferation rates present less clear patterns regarding the importance of packaging materials. The two samples exhibiting the lowest proliferation rates were the two (raw and roasted) stored in PPB at 4°C, marginally outperforming the roasted sample in HBB stored under the same TEMP. The roasted samples in PPB considerably outperformed their raw counterparts across conditions of TEMP and RH except for the sample stored at 4°C. Roasting may produce Maillard reaction products of antioxidant potential, and the data may be exhibiting this antioxidant effect. The samples in UC generally performed poorly (exhibited relatively high proliferation rates).

For TBARS, a marker of secondary lipid oxidation, proliferation rates show no clear associations with packaging materials, TEMP or RH. Generally, the raw samples showed lower TBARS proliferation rates than their roasted counterparts. One notable exception to this is the sample stored in UC at 4°C, as this showed a TBARS proliferation rate (0.011/month) more than two times greater than the next highest proliferation rate. This observation suggests that storage in UC high RH can lead to relatively rapid oxidative degradation of stored almonds.

For FFA, which is also an indicator of lipid degradation, the samples in UC generally showed high rates of increase. The second highest proliferation rate was observed in the raw sample stored in UC at the highest storage TEMP (35°C, 65% RH; rate of 0.11 acid value increase/month), and the highest proliferation rate (0.29/month, more than 2.6 times that of the second highest rate) was observed for the sample stored in UC at 4°C. When viewed in combination with the oxidation data discussed above, the data suggests that storage in UC leads to relatively rapid lipid degradation. When comparing the raw and roasted samples stored in PPB, the raw samples show a consistent and substantial trend of lower FFA production at lower TEMP. The highest rate for these raw samples (0.079/month, at 35°C/65% RH) is more than five times greater than the lowest rate (0.015/month, at 4°C). The roasted samples in PPB exhibit a similar pattern, but it is neither as consistent nor as substantial. The
proliferation rates for these samples range from 0.020/month to 0.039/month. This suggests the proliferation of FFA in roasted samples stored in PPB may be less affected by TEMP than their raw counterparts.

For MC and $a_w$, samples stored in UC demonstrated relatively high proliferation rates for both measures, while the samples stored in HBB showed the lowest proliferation rates of all samples. By contrast, the samples stored in UC at uncontrolled RH showed substantially higher rates of MC/month and $a_w$/month (1.1/month and 0.11/month, respectively), rates 17 and 6.5 times higher than the rates observed in samples stored in HBB under the same TEMP and RH conditions. For the raw and roasted samples stored in PPB, samples generally performed better than those in UC and worse than those in HBB. There is also a clear trend that rates of increase are lower for samples stored under lower TEMP and RH conditions. There is minimal distinction regarding the difference in $a_w$ proliferation rates between raw and roasted samples. For MC, the proliferation rates for raw samples are consistently higher than for their roasted counterparts – suggesting roasting may inhibit moisture uptake.

Predictive models of proliferation rates for raw and roasted almonds in PPB

The results of the multivariable models to predict the observed proliferation rates for all chemical measures within raw and roasted samples in PPB are given in Table 2. TEMP exclusively had positive coefficients in these models, showing the proliferation rates of these chemical markers increase with increased exposure to TEMP.

The quantitation found in these models could be very useful for industry members in the determination of optimised storage conditions. For example, the proliferation rate of PV in almond samples stored in PPB can be expected to increase by $4.4 \times 10^{-3}$ meq. active $O_2$/kg oil/month with each increasing 1°C of storage temperature (within the range of assessed TEMP). Such numerical estimates can be considered by industry members against practical concerns (cost, logistics, etc.) for successful almond storage.

Notably, the coefficient of the “roasted” variable was negative in all models except for that of TBARS. This suggests the process of roasting is exhibiting an effect of...
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Table 2 Summary of multiple linear regression models of monthly proliferation rate of test parameters on raw and roasted almonds stored in PPB

| Parameter | Linear regression coefficients | \( R^2 \) (adj) |
|-----------|-------------------------------|-----------------|
| PV/\( \text{month} \) | Intercept: \( 8.0 \times 10^{-2} \), TEMP (\( ^\circ \text{C} \)): \( 4.4 \times 10^{-3} \), Raw/Roasted: \(-3.7 \times 10^{-2} \) | 79.5% |
| CD/\( \text{month} \) | Intercept: \(-1.4 \times 10^{-1} \), TEMP (\( ^\circ \text{C} \)): \( 8.9 \times 10^{-3} \), Raw/Roasted: \(-1.7 \times 10^{-1} \) | 61.1% |
| TBARS/\( \text{month} \) | Intercept: \( 2.2 \times 10^{-3} \), TEMP (\( ^\circ \text{C} \): \( 1.3 \times 10^{-3} \, \text{meq. active O}_2/\text{kg oil} \) | 49.4% |
| FFA/\( \text{month} \) | Intercept: \( 1.5 \times 10^{-2} \), TEMP (\( ^\circ \text{C} \): \( 1.3 \times 10^{-3} \), Raw/Roasted: \(-1.7 \times 10^{-2} \) | 66.3% |
| MC/\( \text{month} \) | Intercept: \( 1.7 \times 10^{-2} \), TEMP (\( ^\circ \text{C} \): \( 6.2 \times 10^{-3} \), Raw/Roasted: \(-1.0 \times 10^{-1} \) | 79.8% |
| \( a_v/\text{month} \) | Intercept: \( 2.0 \times 10^{-2} \), TEMP (\( ^\circ \text{C} \): \( 8.2 \times 10^{-4} \), Raw/Roasted: \(-2.5 \times 10^{-3} \) | 71.6% |

*Following bimonthly assessments over 16-month of storage, the “proliferation rate” of each “sample” (specific combinations of the factors of RH, temperature and roasting; \( n = 3 \)) was determined by modeling the slope (over months) of the best-fit line through the origin. The models reported here are multivariable models for the prediction of these “proliferation rate” slopes. Models were made using “Best Subsets” modeling, with selection of final models made according to greatest adjusted \( R^2 \). SAS (SAS version 9.4, SAS Institute, Inc., Cary, NC, USA) was used for all modeling.

\( ^a \)A binary term for which \([0 - \text{almonds stored raw} \] and \([1 - \text{almonds stored prior to storage}] \)

\( ^b \)meq. active \( \text{O}_2/\text{kg oil} \).

\( ^c \)Omitted from model due to failure to improve model according to adjusted \( R^2 \).

\( ^d \)Acid value.

preservation within the almonds. By examining the magnitude of the coefficients, we can evaluate the roasting process associated with a reduction in PV proliferation approximately equivalent to a reduction in storage TEMP of 8.4 \( ^\circ \text{C} \) (as calculated as the ratio of the coefficients of the respective variables). Comparisons of similar magnitudes can be made for the other measures. As stated in the introduction, the role of roasting could plausibly be detrimental to stability (due to increased degradation in heat), beneficial to stability (due to the formation of antioxidant products), or a combination of both. The observed effects of improved stability associated with roasting here are therefore notable. The roasting may be producing Maillard reaction products that are exhibiting antioxidant activity within the system (Morales & Jiménez-Pérez, 2001; Lin et al., 2016).

Predictive models of proliferation rates for raw almonds stored in PPB and UC

The results of the multivariable models to predict the observed proliferation rates for all chemical measures within raw samples in PPB and UC are provided in Table 3. As expected, TEMP had positive coefficients, indicating proliferation rates increased with increased TEMP.

Of note here is the observed effect of storage in PPB, which possessed negative coefficients in all significant models. This strongly suggests the storage of almonds in PPB, rather than UC, improves the stability of raw almonds. These models can be used to make quantitative assessments of how this preservation benefit compares to that of changes in TEMP. A comparison of coefficients for the model of PV/month suggests storage in PPB (rather than UC) is associated with reduced PV proliferation rate at a magnitude approximately comparable to reduced storage TEMP of 18.4 \( ^\circ \text{C} \) (within the range of assessed TEMP). Such results indicate the substantial benefit of storage in PPB rather than UC and suggest that such packaging should strongly be considered.

Table 3 Summary of multiple linear regression models of monthly proliferation rate of test parameters on raw almonds stored in PPB and UC

| Parameter | Linear regression coefficients | \( R^2 \) (adj) |
|-----------|-------------------------------|-----------------|
| PV/\( \text{month} \) | Intercept: \( 1.7 \times 10^{-1} \), TEMP (\( ^\circ \text{C} \): \( 2.5 \times 10^{-1} \), Raw/Roasted: \(-4.6 \times 10^{-2} \) | 53.0% |
| CD/\( \text{month} \) | Intercept: \( 1.6 \times 10^{-2} \), TEMP (\( ^\circ \text{C} \): \( 9.9 \times 10^{-3} \), Raw/Roasted: \(-9.9 \times 10^{-3} \) | 38.1% |
| TBARS/\( \text{month} \) | Intercept: \( 5.4 \times 10^{-1} \), TEMP (\( ^\circ \text{C} \): \( -2.3 \times 10^{-1} \) | 28.8% |
| FFA/\( \text{month} \) | Intercept: \( 6.3 \times 10^{-2} \), TEMP (\( ^\circ \text{C} \): \( -2.5 \times 10^{-2} \) | 33.7% |

*Following bimonthly assessments over 16-month of storage, the “proliferation rate” of each “sample” (specific combinations of the factors of temperature, humidity, and roasting; \( n = 3 \)) was determined by modeling the slope (over months) of the best-fit line through the origin. The models reported here are multivariable models for the prediction of these “proliferation rate” slopes. Models were made using “Best Subsets” modeling, with selection of final models made according to greatest adjusted \( R^2 \). SAS (SAS version 9.4, SAS Institute, Inc., Cary, NC, USA) was used for all modeling.

\( {a} \)A binary term for which \([0 - \text{almonds stored raw in UC}] \) and \([1 - \text{almonds stored in PPB}] \)

\( {b} \)Omitted from model due to failure to improve model according to adjusted \( R^2 \).

\( {c} \)Acid value.

\( {d} \)Models were not reported if model had no significant factors (\( \alpha = 0.05 \)).

Predictive models of proliferation rates for roasted almonds stored in PPB and HBB

The results of the multivariable models to predict proliferation rates for all chemical measures within roasted samples in PPB and HBB are reported in Table 4. As with the other multivariable models, TEMP had positive coefficients in these models, showing the proliferation rates of these chemical markers increase with increased TEMP.

Worth noting is the effect of HBB packaging relative to PPB. Our models indicate the use of HBB is
Table 4 Summary of multiple linear regression models of monthly proliferation rate of test parameters on roasted almonds stored in PPB and HBB

| Value      | Intercept | TEMP (°C) | PPB/HBB | R² (adj) |
|------------|-----------|-----------|---------|---------|
| PV/month   | 7.1 × 10⁻² | 3.1 × 10⁻³ | −7.3 × 10⁻² | 75.2%   |
| CD/month   | 1.4 × 10⁻¹ | 9.0 × 10⁻⁴ | ...d     | 37.2%   |
| TBARS/month| No reported models⁷ |         |         |         |
| MC/month   | 1.0 × 10⁻¹ | 4.5 × 10⁻³ | −1.1 × 10⁻¹ | 72.1%   |
| FFA/month  | No reported models⁷ |         |         |         |
| αw/month   | 2.4 × 10⁻² | 5.1 × 10⁻⁴ | −1.6 × 10⁻² | 78.2%   |

*Following bimonthly assessments over 16-month of storage, the “proliferation rate” of each “sample” (specific combinations of the factors of RH, temperature and roasting; n = 3) was determined by modeling the slope (over months) of the best-fit line through the origin. The models reported here are multivariable models for the prediction of these “proliferation rate” slopes. Models were made using “Best Subsets” modeling, with selection of final models made according to greatest adjusted R². SAS (SAS version 9.4, SAS Institute, Inc., Cary, NC, USA) was used for all modeling.

1 A binary term for which [0 = almonds stored in PPB] and [1 = almonds stored in HBB].
2 meq. active O₂/kg oil.
3 Omitted from model due to failure to improve model according to adjusted R².
4 Acid value.
5 Models were not reported if model had no significant factors (α < 0.05).

associated with a reduction in the proliferation rates of PV, MC, and α. These findings qualitatively correspond with those of a 2016 study comparing these packaging materials for the storage of peanuts (Martin et al., 2016), which found higher rates of peroxide formation and more rapid mold increase for the samples stored in PPB. The greater increases in α in PPB in our study may at least partly explain the greater mold increase observed in that 2016 study.

An examination of the coefficients in our models suggests the use of HBB (rather than PPB) is associated with a reduction in expected PV increase by a magnitude comparable to a reduction in TEMP of 23.5 °C. For MC, the reduction in rate is comparable to that of a reduction in 24 °C. For α, the reduction in rate is comparable to that of a reduction in 31 °C. The observed effects of utilising HBB (rather than PPB) to inhibit chemical degradation suggest this packaging should be strongly considered when practical.

Conclusion

Temperature and relative humidity are very important factors to the stability of almonds in storage, with higher TEMP and higher RH both consistently associated with more rapid physicochemical degradation. Samples stored at the lowest assessed TEMP (4 °C) exhibited greater stability than those in higher TEMP. Samples stored at 50% RH exhibited greater stability than those stored at 65% RH. Our study found the roasting of almonds to improve product stability when packaged in PPB. Packaging of raw almonds in PPB, rather than UC, demonstrated substantial improvements in stability as measured by PV, MC and α. Storing roasted almonds in HBB, rather than PPB, was associated with substantially improved stability as measured by PV, MC and α. Our data suggest that HBB are a superior packaging choice, followed by PPB, with UC being associated with the greatest rates of degradation. The choice of packaging will be dictated by economics and the storage conditions to which the almonds are subjected. The predictive models of degradation rates can be used to compare expected quantitative effects of common industry-practice storage factors. It is suggested these predictive models be reviewed when determining appropriate storage strategies for almonds. Further investigations that examine microbial levels, factors for food safety and additional chemical examinations may also be warranted.

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Conflict of interest

The authors declare that they have no conflict of interest.

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