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Publication Date
2023-11-01

DOI
10.1016/j.biosystemseng.2023.10.003

Peer reviewed

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/issn/15375110

Research Paper

Drying of freshly harvested almonds using a stockpile heated and ambient air dryer (SHAD) with an air distributor -part 2

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ARTICLE INFO

Article history:
Received 22 March 2023
Received in revised form 27 September 2023
Accepted 3 October 2023

Keywords:
Energy
Post-harvest
Dehydration
Tree nuts
Quality parameters
Conventional drying

An almond stockpile heated and ambient air dryer (SHAD) without an air distributor, did not adequately distribute air throughout the stockpile. Therefore, this project evaluated the effect of adding an air distributor within the SHAD A-frame as an alternative method to conventional windrow drying. Three stockpile drying tests were performed using ‘Nonpareil’, ‘Winter’, and ‘Monterey’ almond varieties with different initial (fresh) weights and kernel dry-basis moisture contents (MC) equal to 4763 kg and 11.8%, 2585 kg, and 11.5%, and 6849 kg and 21.5%, respectively. All tests were directly compared to conventional windrow drying. Almond quality parameters, including kernel MC, color, lipid oxidative stability, peroxide value, free fatty acid content, internal cavities, and insect injury were measured before and after drying. The SHAD with the air distributor properly maintained almond quality, while uniformly dehydrating almonds to the desired MC of ≤6 % within 7 days. Conventional windrow drying took up to 13.6 days, and the desired final MC was only achieved with the ‘Monterey’ variety. Thus, the SHAD fitted with a well-designed air distributor can be used to dehydrate almonds in a stockpile as an alternative to conventional windrow drying.

1. Introduction

A previous study described the development and performance evaluation of a stockpile heated and ambient air dryer (SHAD) as an alternative to conventional windrow drying for almonds (Mayanja et al., 2021). However, results showed that the drying air produced by the SHAD without an air distributor was unevenly distributed within the stockpile. Thus, there was a need

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https://doi.org/10.1016/j.biosystemseng.2023.10.003

Abbreviations

COP	Coefficient of performance
Mo	Monterey almond variety
Np	Nonpareil almond variety
SHAD	Stockpile heated and ambient air dryer
Wi	Winter almond variety

Symbols

A	Area of pipe (m^2)
$a*$	Green/magenta chromatic axis
$b*$	Blue/yellow chromatic axis
COP	Coefficient of performance
COP	Coefficient of performance (%)
FFA	Free fatty acid content (%)
h	Specific enthalpy (J kg^{-1})
HSD	Honest Significant Difference
IT	Induction time
$L*$	Lightness
m	Molar mass (kg mol^{-1})
MC	Dry basis moisture content (%)
MER	Moisture extraction rate
n	Number of moles
N	Number of outlets
θ	Angle of outlet (°)
P	Pressure (Pa)
PV	Peroxide value (meq kg^{-1})
Pv	Velocity pressure (Pa)
Q	Airflow (m^3 s^{-1})
R	Gas constant (J K^{-1} mol^{-1})
RH	Relative humidity (%)
RMSE %	Root mean square error (%)
SD	Standard deviation
SMER	Specific moisture extraction rate
T	Air temperature (°C)
t	Time (s)
V	Airspeed at outlet (m s^{-1})
ΔE –	Color difference
ρ	Density of air (kg m^{-3})

to design and fabricate an air distributor to enhance the SHAD's air distribution and overall efficiency, as explicitly described in part 1 of this study (Mayanja & Donis-González, 2023).

Numerous studies have documented the application of air distribution to the drying systems of various foods. Grain batch and continuous flow bin batch dryers for crops such as corn, rice, millet, and sorghum commonly contain a perforated plenum at the bottom of the drying bins (Lawrence et al., 2015). Noyes (2006) used a horizontal configuration to distribute the drying air horizontally and uniformly, where a perforated plenum chamber containing multiple outlets was introduced in the center of the drying bin. The latter was based on the principle that a larger volume of air can be forced horizontally across a bin compared to vertically forcing the air while using the same fan power (Day & Nelson, 1965). A similar design was used by Alam et al. (2016) where a vertical concentric perforated plenum chamber was introduced, and an axial fan was placed at the top of the plenum chamber to force the drying air through the grain horizontally.

In almonds, the air distribution concept is applied in drying bins or stadium dryers with a perforated plenum at the bottom. Additionally, Chilka and Ranade (2019) developed an almond tray dryer with a centrifugal fan that draws ambient air into the dryer while perpendicularly exhausting the air through the outlet. The tray dryer had 6 heating coils that could regulate the drying air temperature. Furthermore, Fielke and Coates (2017) conducted on-farm almond mechanical drying studies, exploring the use of eight equally spaced fans blowing ambient air into the false floor of a shed drying facility, the use of a shipping container with a fan on the side, blowing air through the almonds horizontally; and open-ended triangular A-frame across the center of a stockpile with a fan on each end blowing ambient air into the stockpile. The latter system did not control the direction of airflow, especially in the middle section of the stockpile.

No studies were found where a stand-alone air distributor has been developed and evaluated as an addition to almond stockpile drying or a similar application. So, in this study (part 2), the effect on energy consumption, drying, and almond quality was evaluated by placing the air distributor within the SHAD A-frame underneath the almond stockpile. The aim was to improve the efficiency of the SHAD. Thus, three almond stockpile drying experiments were performed on 'Nonpareil'(Np), 'Winter'(Wi), and 'Monterey'(Mo) varieties with initial (fresh) weights and kernel moisture contents measured on a dry basis (MC) equal to 4763 kg and 11.8%, 2585 kg and 11.5%, and 6849 kg and 21.5%, respectively. Stockpile drying tests were directly compared to conventional windrow drying. In addition, almond quality parameters, including MC, color, lipid oxidative stability, peroxide value (PV), free fatty acid (FFA) content, molds or decay, internal cavities, and insect injury were measured before and after drying.

Color is a food quality sensory attribute that is essential to a consumer's judgment and food acceptability such as flavor, and texture, which can be used as a predictor for non-quality attributes like MC, over-processing, and pigment content (Clydesdale, 1991). Furthermore, almond color is a key determinant factor in defining quality grade. According to the U.S. Standards for Grades of Almonds in the Shell, a kernel having dark stains contrasting with the natural color of skin and brown spots greater than 3.2 mm is considered damaged (USDA, 2013). Almond color damage can be partly attributed to drying, especially at high temperatures. Coates (2018) indicated that drying almonds above 60 °C leads to skin flaking or detachment of the kernel pellicle. Also, Rogel-Castillo et al. (2017) stated that drying almonds at above 75 °C leads to internal kernel browning. Kernel browning is typically caused by the Maillard reaction, which is prevalent at high temperatures (Davies & Labuza, 1997).

Lipid oxidation or rancidity occurs when free radicals react between fatty acids and oxygen, resulting in the degradation of lipids (Addis, 1986). Rancid flavor and odour are detrimental to food quality (Buransompob et al., 2003; Vieira et al., 2017). Almonds are prone to rancidity due to their total lipid content which is about 50% (Lin et al., 2012; USDA-ARS, 2015). Rancidity in almonds can be determined using an oil oxidation stability test, which determines the time it takes for the almond oil to resist oxidation, known as induction time (IT) (Läubli & Bruttel, 1986; Sewald & DeVries, 2003). Peroxides are compounds formed during lipid oxidation. PV represents the peroxide concentration and are a typical industry measurement of rancidity (Paramount Farms, 2000). Ideally, a low PV value shows low lipid oxidation, but PV values can also rise and immediately decline as peroxides break down during the later stages of oxidation (Seward & DeVries, 2003). This implies that PV is only valid at the early stages of oxidation and a low PV is not often a representation of low rancidity. Nonetheless, PV can be informative if measured with other lipid oxidative quality parameters, such as FFA content. FFAs are formed by lipid hydrolysis and are unstable, making them prone to oxidation. Therefore, FFAs are also used as indicators for rancidity (Mahesar et al., 2014).

2. Methods

2.1. Drying (stockpile and conventional windrow) tests overview

2.1.1. Sample preparation

The study was conducted at Nickels Soil Laboratory (Arbuckle, CA, USA) for 3 tests which included 'Np', 'Wi', and 'Mo' almond varieties. Each drying test consisted of the stockpile and conventional windrow drying treatments, conducted in parallel. For each test, forty-two fresh almond samples were randomly selected and placed in labeled mesh bags each weighing about 2 kg. Twelve samples were immediately transported to the Postharvest Engineering laboratory. University of California, Davis, USA to measure the initial MC and quality parameters. A wireless data logger (El-USB-2, Lascar Electronics Co, Erie, PA, USA) that recorded temperature (T) and relative humidity (RH) every 5 min was placed in each of the remaining 30 mesh bags containing almond samples to monitor drying conditions in the stockpile and conventional windrow drying treatments. Data loggers had an accuracy level of ±0.3 °C (T) and ±2.25 % (RH), while their measurement range spanned from −35 to 80 °C (T) and 0–100 % (RH). Data loggers were positioned at the approximate centroid of each mesh bag sample, effectively enveloped by almonds to shield them from the environment. Each treatment (stockpile and conventional windrow drying) contained 15 mesh bags, randomly distributed to provide an appropriate representation of the entire almond population and drying process.

2.1.2. SHAD equipment, air distributor placement, airflow distribution, and drying conditions

A mobile stand-alone SHAD system and weather station were the same equipment as reported in Mayanja et al. (2021), with the addition of the air distributor within the SHAD A-frame, as depicted in Fig. 1a & b. Part 1 of this study focused on developing the air distributor as an additional component for the SHAD to improve air delivery throughout the stockpile. The air distributor consisted of 12 outlets grouped into 4 rows, as shown in Fig. 1a. The air percentage delivery from the distributor was 4.1, 30.8, 44.9, and 20.2 % for outlets in rows 1 through 4 (Mayanja & Donis-González, 2023). Considering the characteristic almond cone-shaped stockpile, strategic placement of the air distributor was considered with the objective of achieving effective drying air distribution. This led to positioning the outlets in row 1 at the periphery of the SHAD A-frame, as shown in Fig. 1b. The rationale underlying the air distributor placement stemmed from the predominant concentration of almonds in the middle section of the stockpile. Consequently, outlets in row 3, with the highest airflow (44.9 %), delivered air to the middle portion of the stockpile, while outlets in rows 2 and 4 delivered air to almonds on the stockpile edges. A 304 stainless steel duct of 152.40 mm diameter was used to connect the propane-heated fan in the SHAD to the air distributor. The duct contained an embedded T/RH sensor (HX94C, Omega Engineering Inc, Norwalk, CT, USA) 2.2 m from the fan, with an accuracy level of ±0.6 °C (T) and ±2 % (RH) and measurement ranges from 0 to 100 °C (T) and 3–95 % (RH).

A pitot tube (DS 300 flow sensors, Dwyer Instrument Inc, Michigan City, IN, USA) was inserted inside the duct connecting the fan outlet to the air distributor, 2.5 m away from the fan to measure the airflow under approximate laminar flow. A pressure sensor (Series MS Magnesense, Dwyer Instruments Inc, Michigan City, IN, USA) was connected to the pitot tube to record the static and total pressure. The difference between total and static pressure yielded the velocity pressure (P_v). Ultimately, airflow (Q) was calculated in $m^3\ s^{-1}$ using Eqs. (1) and (2) (Cengel & Cimbala, 2017).

$$V = \sqrt{\frac{2P_v}{\rho}} \tag{1}$$

$$Q = AV \tag{2}$$

Where V is the velocity of airflow ($m\ s^{-1}$), A is the area of the duct (m^2) or 0.018 m^2

ρ is the density of air ($kg\ m^{-3}$).

The heated drying T averaged over the drying period was 57.2 °C ('Np'), 54.5 °C ('Wi'), and 56.5 °C ('Mo'), and ambient drying T was 30.2 °C ('Np'), 23.9 °C ('Wi'), and 26.7 °C ('Mo'), which were used to calculate the density of air (ρ), as stated in Eq. (3) (Dickerson et al., 1979). The drying T was generated from the T/RH sensor placed within the samples, as described earlier. T values for periods when the heater was on corresponded to heated drying T and the remaining to ambient drying T.

$$\rho = \frac{P\,m}{n\,R\,T} \tag{3}$$

Where P is atmospheric pressure (101,325 Pa), m is the molar mass of air (0.02896 $kg\ mol^{-1}$), n is the number of moles (taken as 1 to match units of molar mass) and R is the gas constant (8.3145 $J\ K^{-1}\ mol^{-1}$).

2.1.3. Almond drying and sample distribution

Almonds were directly dropped onto the A-frame from the harvesting conveyor cart (Fig. 1c), containing a built-in weighing scale to record the almond weight, until about a third of the desired height and weight was achieved to form the bottom layer. Five almond sample mesh bags with embedded T/RH sensors were evenly distributed on the partial almond stockpile. The procedure was repeated for the middle (about two-thirds of the stockpile height and weight) and top layers (final height and weight). A visual representation of the layers can be observed in Fig. 1d. Stockpile dimensions (l x w x

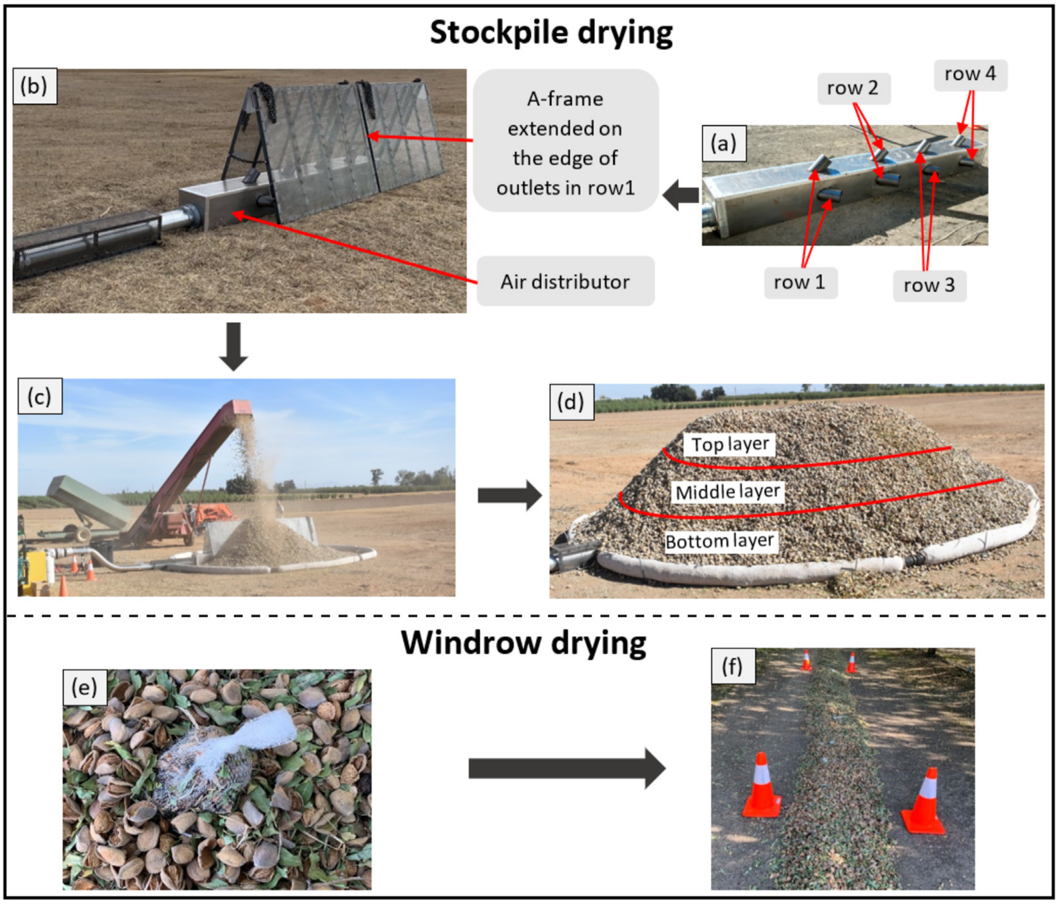

Fig. 1 – (a) Air distributor and the categorization of outlets into rows 1 to 4, (b) air distributor placed underneath the A-frame, (c) conveyer cart dropping almonds on the A-frame to form a stockpile, (d) stockpile split into the bottom, middle, and top layers, (e) sample mesh bag with almonds placed in a windrow, (f) almond windrow.

h) for the 'Np', 'Wi', and 'Mo' drying tests were 4.9 x 3.6 × 1.6 m, 3.6 x 2.4 × 1.5 m, and 7.3 x 4.9 × 1.6 m at a weight equal to 4,763, 2,585, and 6849 kg, respectively. In parallel, three adjacent almond windrows were established in an almond field (Fig. 1e & f), next to the stockpile tests, to mimic and monitor conventional windrow drying. Each windrow contained 5 almond samples in mesh bags with embedded T/RH sensors. After each drying test, all the samples from the stockpile ($n = 15$) and windrows ($n = 15$) were immediately transported to the post-harvest engineering laboratory at UC Davis to test for final MC and quality parameters.

2.2. *Sample dry-basis moisture content (MC) determination*

Five almonds were randomly chosen from each mesh bag sample. Subsequently, the hulls and shells were manually removed, after cracking the shell using a hammer. Almond kernels were then placed in 70 mm diameter aluminium crimped-walled weighing dishes (Cole-Parmer Instrument Co., Vernon Hills, IL, USA.). MC dry basis, expressed as a percentage, was calculated using the oven drying method after drying the almond kernels inside an oven at 105 °C for 24 hrs, as specified by Helrich (1990).

2.3. *Energy consumption, cost, and dryer performance indicators*

Total energy consumption (electrical and propane), energy cost, and dryer SHAD performance indicators including specific moisture extraction rate (SMER), moisture extraction rate (MER), and coefficient of performance (COP) were determined as described by Mayanja et al. (2021).

2.4. *Quality parameters*

2.4.1. *Color measurement changes*

Color was measured both inside and at the surface of the kernel with a spectrophotometer (Colorflex EZ, Hunter Associates Laboratory Inc, Reston, VA, USA) using the three-dimensional CIE color space: lightness (L^*), green/magenta (a^*), and blue/yellow (b^*) chromatic axes (CIE, (1986). Nine almond kernels were randomly selected from each sample mesh bag and longitudinally dissected using a sharp knife, then placed on the spectrophotometer to assess the kernel's internal color (inside). The procedure was repeated for the kernel's pellicle (surface). Color difference (ΔE) was used to measure the change between freshly harvested almonds (initial) and dehydrated almonds, by stockpile or windrow drying, as shown in Eq. (4) (Minolta, 1994).

$$\Delta E = \sqrt{(L_f^* - L_i^*)^2 + (a_f^* - a_i^*)^2 + (b_f - b_i^*)^2} \quad (4)$$

Where the subscript "i" indicates the color value of the freshly harvested almonds and the color subscript "f" subscript is for dehydrated (final) almonds.

2.4.2. *Almond oil extraction, induction time (IT), peroxide value (PV), and free fatty acid (FFA) content*

Thirty almond kernels were randomly selected from each sample, and ground with a hammer into particles of less than 4 mm using a 4 mm sieve (Gilson Company Inc, Lewis Center, OH, USA). Ground almonds were then pressed to mechanically extract their oil for 5 min in a stainless-steel cylinder (57 mm diameter and 76 mm height) using a hydraulic press (Model 3351 Carver Inc, Wabash, IN, USA) at 5000 N. The extracted oil was filtered using an 11 μm pore size filter paper (GE Healthcare Systems, Chicago, IL, USA). On average, 2 g of almond oil was collected per sample in a stainless-steel pan.

Lipid oxidative stability or IT was conducted using a Metrohm Rancimat Model 892 (Metrohm Ltd., Herisau, Switzerland). Extracted oil of 1.5 g was added to a reaction vessel and heated to 120 °C, while 10 L hr^{-1} of filtered air was forced through the oil (Metrohm, 2017, p. 892). A 1.5 g sample was used rather than the recommended 3g by the manufacturer Metrohm. (2017), due to a low oil yield from samples. Therefore, the IT analysis was intended to determine the relative difference between the drying treatments, since samples were treated similarly.

PV expressed as meq kg^{-1} was determined using the CDR FoodLab (2021a) protocol using a CDR analyzer (CDR FoodLab, CDR s.r.l company, Salerno, Italy) with 25 μl of almond oil. PV of 2 meq kg^{-1} is the upper acceptable limit for almonds (Paramount Farms, 2000; USDA-ARS, 2015).

FFA content was determined following the CDR FoodLab (2021b) procedure using 10 μl of almond oil. FFA equal to 1% oleic acid is the upper acceptable limit for almond rancidity (Mahesar et al., 2014; USDA-ARS, 2015).

2.4.3. *Molds or decay, insect injury and internal cavities*

Ten almonds were randomly selected from each sample to visually assess and quantify damages caused by molds or decay, instances of insect injury, and the presence of internal cavities. The defective almond count was expressed as a percentage in relation to the total sample of ten, as specified in the manual for shipping point and market inspection instructions for almonds (USDA, 1998). The identification of internal cavities was conducted through the observation of split cotyledons after slicing the kernels in half using a knife, a technique consistent with the approach described by Coates (2018). Instances of mold on the almonds were noted when visibly apparent on the kernel, while white or grey mold that could be easily rubbed off was disregarded. Decay was registered if the kernel was found to be partially or completely decomposed (USDA, 1998). In instances of insect injury, the presence of insects, webs, frass, or indications of insect feeding was tallied (USDA, 1998; Schatzki & Ong, 2001).

2.5. *Experimental design, data analysis and visualization*

Data analysis and visualization were performed in R studio (version 1.4.1106) and SAS Enterprise 7.1. Data analysis was divided into three experimental designs:

1) A split-plot design was used for the stockpile (plot) drying tests, where each plot represented a layer (bottom, middle, and top). One-way analysis of variance (ANOVA) was conducted on MC and each quality parameter to determine significant differences between stockpile layers. When a significant main effect was found, a post hoc test using Tukey's Honest Significant Difference (HSD) test was conducted to ascertain the difference of the means within layers, at a 95 % confidence level ($p \leq 0.05$); 2) A similar design and analysis was used for the windrow drying tests, except that each windrow was considered a plot; and 3) A two-sample t-test analysis was conducted to ascertain whether the means of the MC and each quality parameter from the stockpile and windrow drying tests were significantly different. The latter included the calculation of the P-value using the Folded F method to assess whether the two groups had equal or unequal variances. When the P-value of the Folded F was greater than 0.05, it implied that the two groups had equal variances. Thereafter, the pooled method was used to determine whether the two groups were significantly different at $P = 0.05$. Otherwise, if unequal variances were observed, the Satterthwaite method was used to determine whether the two groups were significantly different at $P = 0.05$ (Bhattacharyya, 2013). (In addition, data visualization of the mean T and RH data through drying was conducted as in Mayanja et al. (2021).

3. Results and discussion

3.1. *Airflow distribution, drying conditions and time*

The average airflow of the SHAD with the addition of the air distributor was 1.18 ± 0.28 $m^3\ s^{-1}$ ('Np'), 1.19 ± 0.33 $m^3\ s^{-1}$ ('Wi'), and 1.14 ± 0.29 $m^3\ s^{-1}$ ('Mo'). Therefore, the airflow per volume of fresh almonds was 0.042 ± 0.01 ('Np'), 0.092 ± 0.03 ('Wi'), and 0.02 ± 0.005 ('Mo') $m^3\ s^{-1}$ per m^3. The 'Wi' test had the highest airflow in relation to the quantity of dehydrated almonds, hence dehydrating almonds in less time (6 days) compared to the 'Np' (6.2 days), and Mo (7 days) varieties. Coates (2018) developed a cylindrical tower of 0.3 m diameter and 3 m height to determine the necessary airflow rates to aerate almonds, showing that at a T of 50 °C and 40% RH, almonds should be dehydrated at an airflow of 0.19 $m^3\ s^{-1}$ per m^3 to achieve equilibrium moisture content, which is higher than the airflow achieved in this study. Less airflow during this test can be justified as Coates (2018) conducted the study in a closed environment, ignoring external factors such as wind, which contribute to the dehydration of almonds in a stockpile.

Furthermore, the previous SHAD test without an air distributor had an airflow of 0.078 m^3 s^{-1} per m^3 of fresh almonds, and drying was achieved in 11 days (Mayanja et al., 2021). Two varieties ('Np' and 'Mo') with the addition of the air distributor had a lower airflow per m^3 of almonds than the previous test but still achieved drying in less time. Therefore, the reduction in drying time can mainly be attributed to the improved air distribution through the stockpile, mainly due to the addition of the air distributor.

Figures 2 and 3 show the RH and T profiles for the stockpile and windrow treatments. The set-point for the heated fan was automatically controlled at 55–60 °C. Therefore, the fan was on for 38% ('Np'), 15.3 % ('Wi'), and 25.3 % ('Mo') in relationship to the total drying time, respectively. This resulted in an average T of 57.2 ± 8 °C ('Np'), 54.5 ± 10.4 °C ('Wi'), and 56.5 ± 9.9 °C ('Mo'). The heated fan was turned off during day 6 ('Np'), days 1 and 2 ('Wi'), and days 2, 3, and 4 ('Mo') due to high fire risks in the region, so during this time, almonds were only dehydrated with ambient air. The average recorded ambient T was 30.2 ± 6 °C ('Np'), 23.9 ± 5.8 °C ('Wi'), and 26.7 ± 5 °C ('Mo'), and the average ambient RH was 40.4 ± 14.1 % ('Np'), 36.1 ± 15.1 % ('Wi'), 30.7 ± 12.5% ('Mo').

The previous SHAD test without the air distributor removed 6.6 % of MC in 11 days at 55 °C, under ambient drying T and RH of 18.5 °C and 31.7% respectively (Mayanja et al., 2021). Current stockpile drying tests with the SHAD and the air distributor dehydrated 7.4 % ('Np'), 6.8% ('Wi'), and 17.5 % ('Mo') MC in 6.2 days ('Np'), 6 days ('Wi'), and 7 days ('Mo'). Therefore, the addition of the air distributor to the SHAD reduced the drying time by around half, mainly attributed to an enhanced distribution of air through the stockpile. Even though the ambient T of these tests was higher than the one without the air distributor, this effect can be considered negligible as the bottom and middle layers of the stockpiles were primarily dehydrated by the forced air generated by the SHAD, rather than the surrounding ambient air.

Opposite to the stockpile treatment, conventional windrow drying relied solely on ambient air conditions to achieve dehydration. Windrow tests took 13.6 days ('Np'), 8.8 days ('Wi'), and 12.3 days ('Mo)' to dehydrate the almonds. Therefore, almond windrow drying took longer than the SHAD with the air distributor by a margin of 7.4 days ('Np'), 2.8 days ('Wi'), and 5.3 days ('Mo'). The duration of the windrow drying tests aligns with the findings of Micke et al. (1966), who reported that windrow drying typically takes between 1 and 2 weeks.

3.2. *Energy consumption, cost, and dryer performance indicators*

The total energy consumption for the stockpile treatment was 1130 MJ ('Np'), 1500 MJ ('Wi'), and 1543 MJ ('Mo'). The specific energy required to dehydrate one tonne of water from the almond stockpile was 3214 ('Np'), 8508 ('Wi'), and 1290 MJ kg^{-1} of water ('Mo'). Thus, the specific energy was inversely proportional to the stockpile size, whereby the 'Wi' test used the most energy. This shows that a reduced stockpile size of 2585 kg is below the operation capacity of the SHAD. On the other hand, the largest stockpile ('Mo') utilized the lowest amount of energy. The previous SHAD drying test without an air distributor yielded a specific energy of 5623 MJ kg^{-1} of water, demonstrating that the SHAD utilized more energy than the current 'Np' and 'Mo' tests due to the lack of proper air distribution (Mayanja et al., 2021).

The cost of dehydrating 1 tonne of fresh almonds was 6.5 ('Np'), 15.5 ('Wi'), and 6.4 US $ per kg of almonds ('Mo'). The 'Wi' test reflected the highest energy cost, mainly due to the underutilization of the SHAD. Also, the previous SHAD test without the air distributor yielded a cost of 11.7 US $ per kg, which is higher than the 'Np' and 'Mo' tests, but not the underutilized 'Wi' test.

The SMER for the stockpile treatment was 1.12 kg kWh^{-1} ('Np') [K], 0.42 kg $kW^{-1}h^{-1}$ ('Wi') [E], and 2.78 kg $kW^{-1}h^{-1}$ ('Mo')

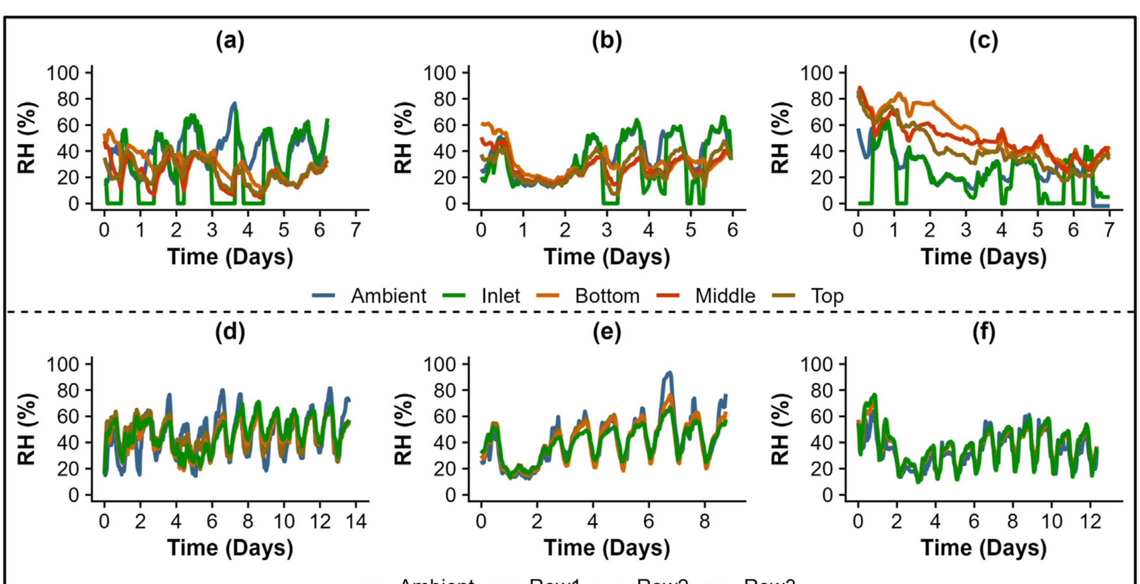

Fig. 2 – RH profile; (a) stockpile ('Np'), (b) stockpile ('Wi'), (c) stockpile ('Mo'), (d) windrow ('Np'), (e) windrow ('Wi'), (f) windrow ('Mo'). It should be noted that in certain cases, the values were identical, leading to indistinguishable profiles for some tests.

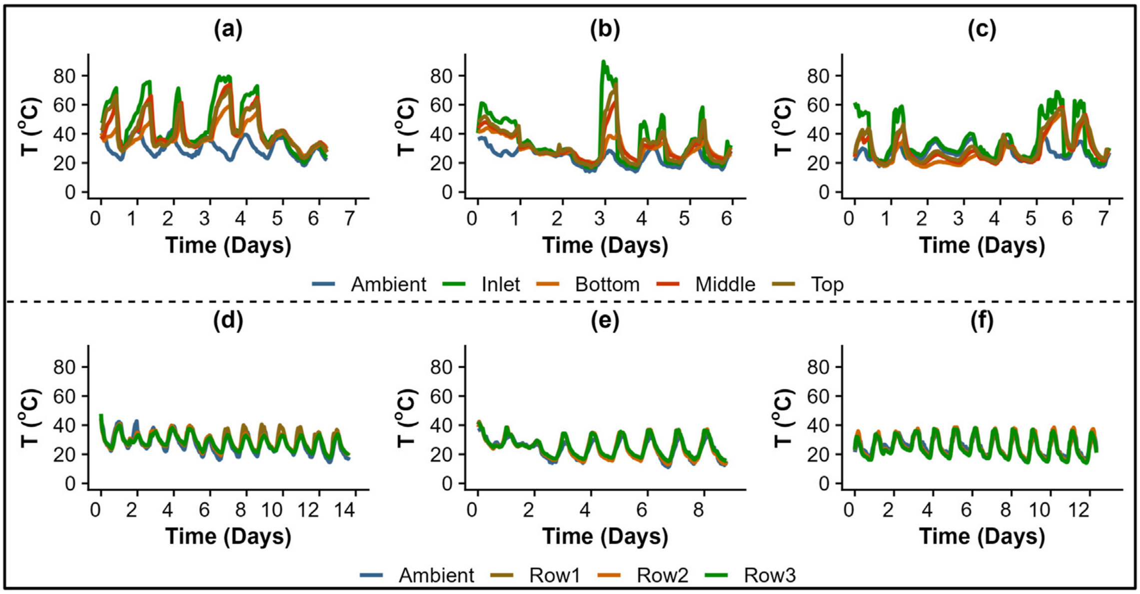

Fig. 3 – T profile: (a) Stockpile ('Np'). (b) Stockpile ('Wi'). (c) Stockpile ('Mo'). (d) Windrow ('Np'). (e) Windrow ('Wi'). (f) Windrow ('Mo'). It should be noted that in certain cases, the values were identical, leading to indistinguishable profiles for some tests.

[M]. SMER describes the effectiveness of energy used during drying (Prasertsan & Saen-Saby, 1998). Therefore, a comparison with existing dryers (Fig. 4a) showed that the supplied energy was effectively used to achieve drying since these values are in the upper limit of energy efficiency. The 'Wi' test was on the lower limit due to the reduced size of the stockpile,

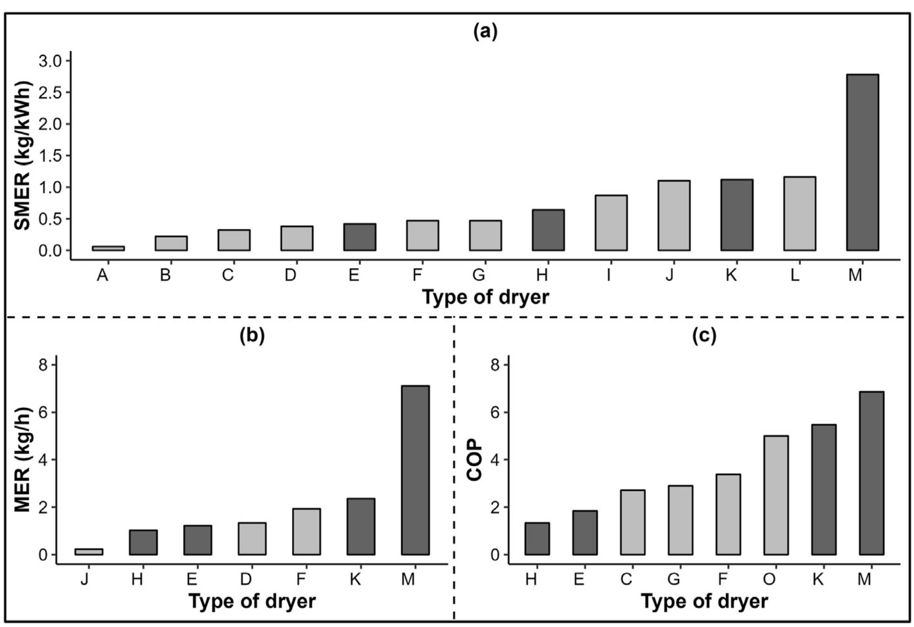

Fig. 4 – (a). Bar plot comparing SMER of different dryers, (b) bar plot comparing MER of different dryers, (c) bar plot comparing COP of different dryers. [A] Closed system heat pump dryer for ginger at 50 °C (Chapchaimoh et al., 2016), [B] Convection solar dryer for bitter gourd (Vijayan et al., 2016), [C] Heat pump dryer for tomato slices at 45 °C (Coskun et al., 2017), [D] Solar dryer for cassava at 40 °C (Yahya et al., 2016), [E] Stockpile heated and ambient air dryer for almonds 'Wi' at 59 °C (this study), [F] Solar assisted heat pump dryer for cassava at 45 °C (Yahya et al., 2016), [G] Solar assisted heat pump for mushrooms at 45 °C (Sevik et al., 2013), [H] Stockpile heated and ambient air dryer (SHAD) without the addition of the air distributor for almond, previous test (Mayanja et al., 2021), [I] Solar dryer for chili at 50 °C (Mohanraj & Chandrasekar, 2009), [J] Heat pump dryer for sweet pepper at 40 °C (Pal & Khan, 2010) [K] Stockpile heated and ambient air dryer for almonds 'Np' (this study) [L] Heat pump assisted hybrid photovoltaic thermal solar dryer for saffron at 45 °C (Mortezapour et al., 2012), [M] Stockpile heated and ambient air dryer for almonds 'Mo' at 55 °C (this study) [O] Heat pump for mint leaves at 45 °C (Ceylan & Gurel, 2016).

showing that some of the drying air escaped the stockpile before it removed moisture from the almonds. Also, comparisons showed that the average SMER of the SHAD tests with an air distributor (1.44 ± 1.2 kg $kW^{-1}h^{-1}$) was higher than the previous test without the air distributor (0.64 kg $kW^{-1}h^{-1}$) [H] with a 125 % increase in energy efficiency (Mayanja et al., 2021).

Furthermore, the SHAD test with the air distributor yielded a MER of 2.36 kg h^{-1} ('Np') [K], 1.22 kg h^{-1} ('Wi') [E], and 7.11 kg h^{-1} ('Mo') [M]. MER was used to measure the dryer capacity (Prasertsan & Saen-Saby, 1998). A comparison with existing dryers (Fig. 4b) showed that the 'Wi' test was dehydrating almonds below its capacity. 'Np' and 'Mo' tests (larger stockpiles) showed high values of MER. The average MER for the SHAD tests with the air distributor (3.56 ± 3.12 kg h^{-1}) was higher than the previous test without the air distributor (1.02 kg h^{-1}) [H] with a 249 % increase (Mayanja et al., 2021).

Additionally, the COP for the stockpile test was 5.47 ('Np') [K], 1.84 ('Wi') [E], and 6.86 ('Mo') [M]. Oktay and Hepbasli (2003) stated that COP is used to evaluate the efficiency of the propane-heated fan. Comparison with existing dryers (Fig. 4c) showed that the fan for the 'Wi' test was not efficient, as it utilised more energy than required to dehydrate the almonds. Thus, 'Np' and 'Mo' tests were more efficient. The average COP for the SHAD tests with the air distributor (4.73 ± 2.59) was greater than the previous test without the SHAD (1.33) [H] with a 255 % increase (Mayanja et al., 2021).

The addition of the air distributor improved the energy efficiency of the SHAD, but only for the 'Np' [K] and 'Mo' [M] tests in comparison to exiting dryers and the SHAD without an air distributor [H] (Mayanja et al., 2021). Future studies will be performed to determine the maximum drying capacity of the SHAD with the air distributor, as well as the effect of increasing the fan size and covering the stockpile to recirculate and better distribute the air through the stockpile.

3.3. *Almond moisture content (MC) before and after drying tests*

The final MC for all stockpile tests was below the target value of 6 %. The 'Mo' variety contained the highest fresh MC of 21.5 ± 2.1 %, followed by 'Np' (11.8 ± 2 %), and 'Wi' (11.5 ± 0.6 %). Figure 5a shows the MC of stockpile layers for the three SHAD drying tests, which showed that the MC in the top layer was significantly higher (p-value ≤0.05) between stockpile layers for both 'Np', and 'Wi' varieties. Also, the Tukey HSD post-hoc test showed that the bottom and top layers were statistically different (p-value ≤0.05) for both 'Np', and the top layer for 'Wi' tests.

The average final MC through the three varieties dehydrated with the SHAD was 4 ± 0.7 %, 4.4 ± 0.9 %, and 4.7 ± 0.7 % for the bottom, middle, and top layers, respectively. Similarly, Chen et al. (2021) dehydrated almonds in a column air dryer and indicated that almonds located at the dying air entry have a lower MC, which increased proportionally to the height. On the other hand, the SHAD without an air distributor had a final MC of 7.1 ± 2.6 % (bottom), 6.4 ± 3.3 % (middle), and 4.6 ± 0.7 % (top) (Mayanja et al., 2021). When the SHAD was used without the air distributor, the MC at the bottom and middle layers was higher than the desired 6 %, and the bottom layer yielded the lowest MC, showing that the SHAD without the air distributor was ineffective. Thus, the use of the air distributor increased the effectiveness of the SHAD and ensured that almonds across stockpile layers were at the desired MC by the end of the drying tests.

In comparison, the windrow tests yielded a highly variable moisture distribution, in some instances above 6 % MC (Fig. 5b). The 'Np' windrow test had an overall average of 17.6 ± 1.5% MC attributed to an unwanted irrigation event, which accounted for the increase in the final MC, relative to the initial MC. Conventional windrow tests were conducted between almond rows following industry practice, which exposes almonds to water if the orchard is mistakenly irrigated. The previous occurrence is rare, but this study demonstrated the potential negative effect of conventionally drying almonds in windrows. The 'Wi' windrow trial had an overall average MC of 6.8 ± 0.6 %, which is undesirable for storage. This can partly be attributed to a precipitation event that occurred leading to the rehydration of the almonds (Uesugi & Harris, 2006). Compared to the 'Np' and 'Wi' windrow tests, the final MC for all the rows in the 'Mo' windrow was below 6 %, which

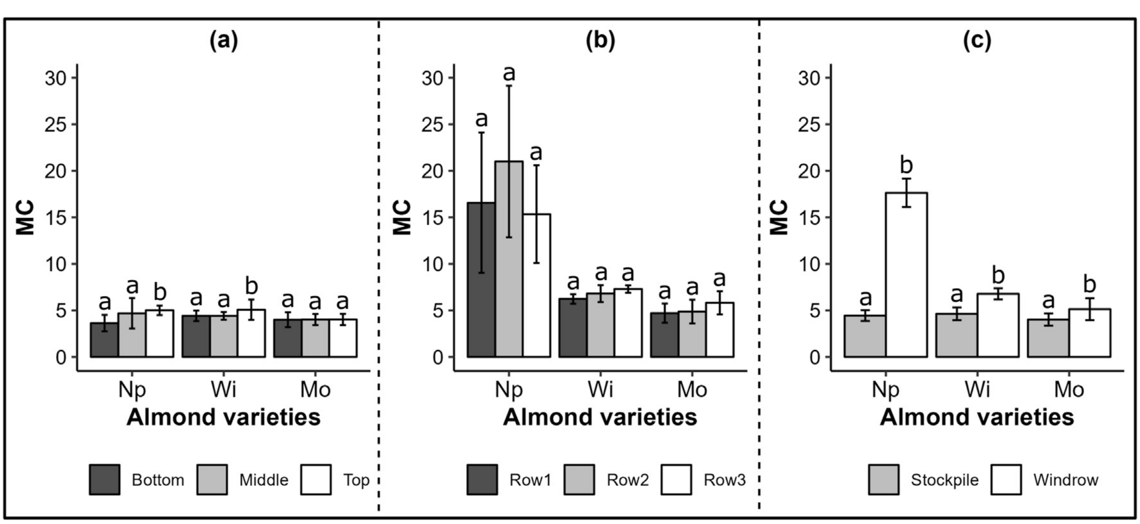

Fig. 5 – Final MC for; (a) stockpile layers; (b) windrows; and (c) stockpile and windrow tests.

is desired. There was no significant difference between the MC across windows in all the varieties, showing that drying occurred similarly regardless of the row.

Figure 5c shows the comparison between mean stockpile and conventional windrow drying tests where a significant difference ($p \le 0.05$) was seen for all the varieties. More specifically, conventional windrow drying was unreliable in terms of attaining the desired MC since it is prone to adverse effects, including rain or unwanted irrigation events, as was the case during the 'Np', and 'Wi' windrow drying tests.

3.4. Quality parameters

3.4.1. Color measurement changes

The average ΔE results for the stockpile and convention windrow treatments for the internal and surface kernel color are shown in Fig. 6a and b, respectively. Relative comparison (t-test) indicated that ΔE of stockpile and windrow treatments were not significantly different. Similar findings were observed when analyzing (ANOVA test) for the difference between the stockpile layers (Fig. 6c and e), and windrows

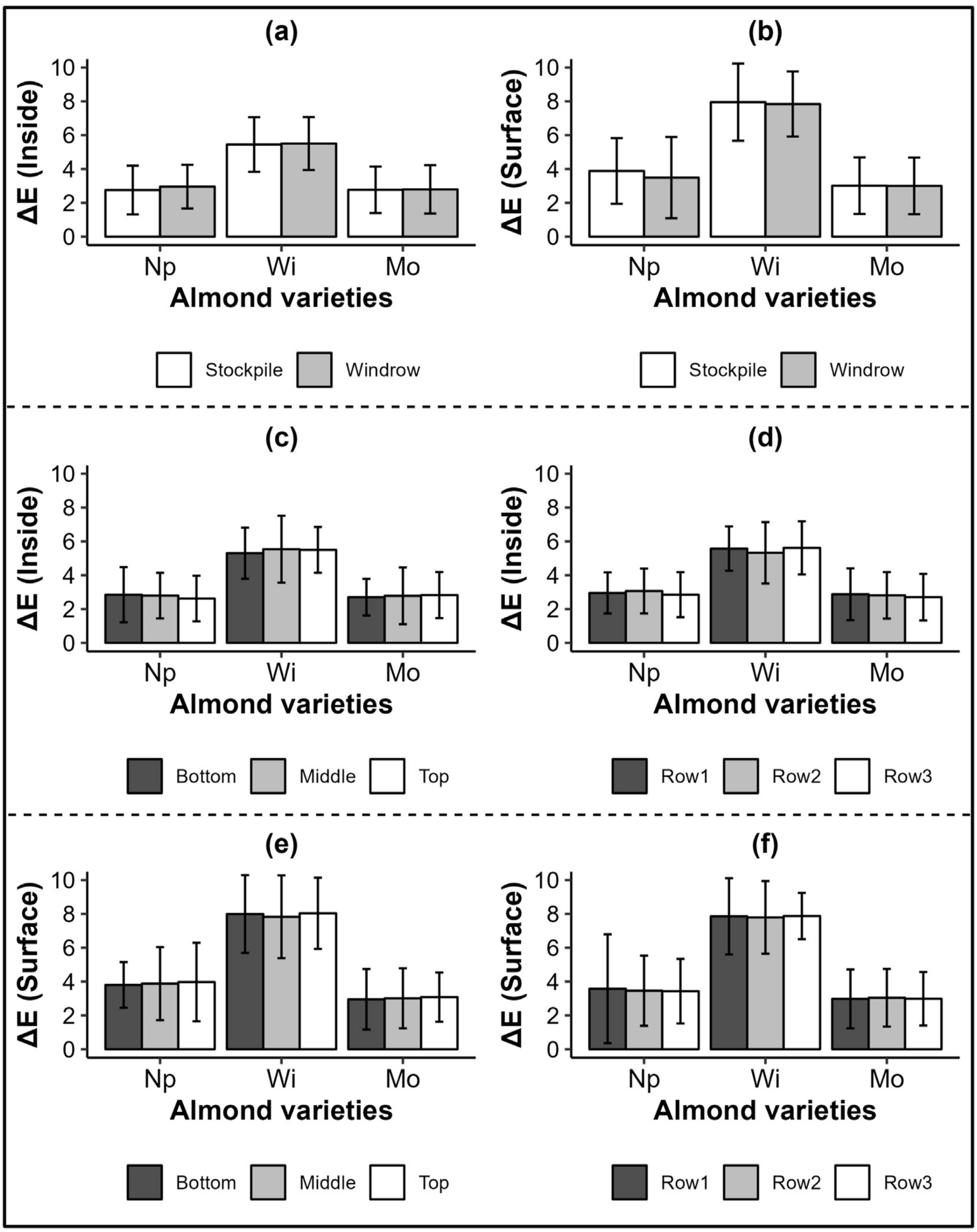

Fig. 6 – Bar plot showing average ΔE results for; (a) inside of stockpile and windrow tests; (b) surface of stockpile and windrow tests; (c) inside for each of the stockpile layers; (d) inside for each of the windrows; (e) surface for each of the stockpile layers; and (f) surface for each of the windrows.

(Fig. 6d and f) at $P \leq 0.05$. The overall averages of ΔE for the stockpile were 3.7 ± 1.5 (inside), and 5 ± 2 (surface), while the ΔE values for the windrow were 3.8 ± 1.4 (inside), and 4.8 ± 2 (surface). Coates (2018) indicated that ΔE develops due to the exposure to heat when dehydrating. Thus, the almond surface hypothetically yielded a higher ΔE because it was exposed to higher temperatures than the inside.

The average ΔE values were 2.9 ± 1.4 ('Np'), 5.5 ± 1.6 ('Wi'), and 2.8 ± 1.4 ('Mo') for the inside, while the surface values were 3.7 ± 2.2 ('Np'), 7.9 ± 2.1 ('Wi'), and 3 ± 1.7 ('Mo'). The difference in ΔE values showed that different almond varieties reacted to heat differently, mainly due to differences in physicochemical properties (Dingke & Fielke, 2014; Yada et al., 2011). The values of ΔE were not a concern or statistically different between the drying treatments.

3.4.2. *Induction time (IT), peroxide value (PV), and free fatty acid (FFA) content*

Lipid oxidation known as IT was not significantly different ($P \leq 0.05$) between stockpile layers (Fig. 7a) and windrows (Fig. 7b). Additionally, the t-test revealed that there was also no significant difference between the stockpile and windrow treatments for all tests (Fig. 7c). Metrohm (2013) reported IT values of 4 hrs with an oil sample equal to 3g, while Capanoglu and Boyacioglu (2008) reported values of 4.2 hrs using 2.5 g of oil. This study yielded an average IT of 5.4 ± 0.3 hrs, and 5.3 ± 0.2 hrs for all varieties in the stockpile, and windrow drying tests, respectively. This 1 h difference from other studies can be partly attributed to the differences in the amount of almond oil used to perform the IT test. Regardless, the relative comparison showed that the effect of rancidity in dehydrating almonds was similar between drying methods, and no statistical differences were observed.

The PV results for the stockpile and windrow treatments are shown in Fig. 7d. Overall, PV results were less than 0.2 meq kg^{-1} throughout, concurring with other studies that yielded PV of 0.34–0.41 meq kg^{-1} (Li et al., 2018), 0.46–0.72 meq kg^{-1} (Uesugi & Harris, 2006) and 0.24–0.49 meq kg^{-1} (Gao et al., 2011). Therefore, negligible levels of peroxides were generated during the drying tests. FFA values from all the tests were below 0.01%, while other studies reported FFA values of 0.18–0.24% (Li et al., 2018), 0.16–0.37% (Uesugi & Harris, 2006), 0.11–0.27% (Gao et al., 2011), implying negligible levels of rancidity. A statistical analysis was not conducted for the PV and FFA results since all results were significantly lower than the maximum acceptable limit of 2 meq kg^{-1} (PV), and 1 % oleic acid, respectively (Buransompob et al., 2003; Paramount Farms, 2000).

3.4.3. *Molds or decay, insect injury and internal cavities*

Freshly harvested almonds contained 0 % ('Np'), 0.3 ± 1.6 % ('Wi'), and 0.3 ± 0.4 % ('Mo') decay or mold damage, which is considered negligible. After drying, decay or mold injury of the 'Np' test was 0.7 ± 1.9 % and 1.3 ± 3.8 % for the stockpile and windrow drying treatments, respectively. Results for the t-test of the 'Np' test showed that there was a significant difference (Satterthwaite P-value <0.5) in decay or molds between the stockpile and windrow treatments, mainly attributed to the

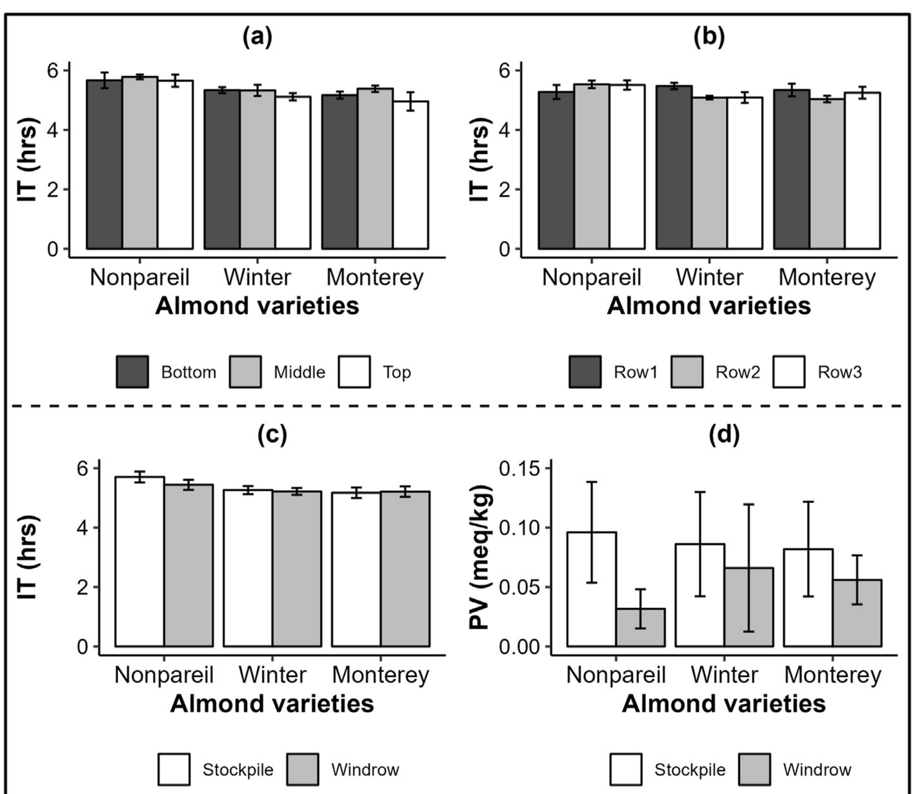

Fig. 7 – Average IT for each of the: (a) stockpile layers; (b) windrows; (c) stockpile and windrow tests. (d) average PV for stockpile and windrow tests.

unwanted irrigation event. In addition, the decay or mold injury percentage for the 'Wi' variety after drying was 0.7 ± 1.4 % (stockpile) and 1.1 ± 1.6 % (windrow). Rain during the 'Wi' test could have contributed to the presence of decay or molds during the windrow test. Also, the 'Mo' test had 0.9 ± 1.5% and 0.4 ± 1.2% for stockpile and windrow drying treatments. The prolonged wetness of almonds and contact with the orchard ground made them susceptible to the development and growth of molds (King et al., 1983). Thus, mold growth can be reduced during stockpile drying, if sweeping and picking of almonds are eliminated. The previous test where almonds were dehydrated with the SHAD but without the air distributor yielded mold or decay damage at 1.8 ± 2.6 %, which was low but can still be attributed to sections within the stockpile that did not receive proper aeration (Mayanja et al., 2021).

Measurable insect injury of fresh almonds was zero. After drying, the SHAD stockpile test with and without the air distributor had no insect damage. Insect damage for the windrow treatment was 0.4 ± 1.2 % ('Np'), 0.2 ± 0.9% ('Wi'), and 0 % ('Mo'). Overall, insect damage for the windrow was low, at below 1%. Nonetheless, almonds in contact with the ground can contribute to the presence of insect damage and its associated adverse effects such as aflatoxins (Campbell et al., 2003; King et al., 1970), which was not the case in almonds dehydrated with the SHAD.

Freshly harvested almonds contained no detectable internal cavities. After drying, 0.1 ± 1.2% ('Np') and 0 % ('Wi' and 'Mo') cavities were recorded for the stockpile treatment. Also, windrow drying showed 0% internal cavities for all the varieties. Internal cavities are an indicator of a fast-drying rate, caused by the solidification of the outer surface of the almond kernel, hence causing it to split (Coates, 2018). Further, Chen et al. (2020) dehydrated almonds at 40–60 °C in a column dryer and reported 0 % internal cavities. Therefore, drying almonds by both treatments produced negligible or no kernel splitting. In contrast, the previous SHAD test without the air distributor resulted in internal cavities of 1.8 ± 2.7 %, which is still considered a low value (Mayanja et al., 2021).

4. Conclusion

Drying almonds with a combination of SHAD and an air distributor took a shorter period (maximum of 7 days) compared to the test without an air distributor (11 days) (Mayanja et al., 2021). Also, the desirable MC (<6 %), internal cavities (0.2%), decay or mold injury (<0.9%), PV (<0.2 meq kg^{-1}), and FFA (<0.01% Oleic acid) were accomplished across all SHAD stockpile tests. Furthermore, the relative comparison (t-test) of ΔE and IT values of stockpile versus conventional windrow treatments showed no significant difference, which was also desirable. On the other hand, conventional windrow drying took up to 9.5 days, and the desired final MC was only reached during the 'Mo' trial. The Np' and 'Wi' windrow tests were compromised by irrigation and rain, respectively.

The addition of the air distributor improved the energy parameters by 125 % (SMER), 249 % (MER), and 255 % (COP). A comparison of the energy parameters with existing dryers showed that the 'Np' and 'Mo' tests were either within or above limits. However, the 'Wi' test performed poorly due to the underutilisation of the SHAD. Thus, a SHAD with air distributors can be used to effectively dry almonds in the range of 4763 (0.042 ± 0.01 $m^3\ s^{-1}$ per m^3 of fresh almonds) and 6849 kg (0.02 ± 0.005 $m^3\ s^{-1}$ per m^3). Future work will evaluate the effectiveness of utilizing the SHAD with the air distributor to dehydrate larger almond volumes, as well as the effect of incorporating larger fans, and the addition of a cover to augment air recirculation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work was financially supported by the Almond Board of California (Grant number: HARV1A). The field tests were conducted at Nickels Soil Laboratory, and laboratory analysis at the Department of Biological and Agricultural Engineering, University of California, Davis.

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