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DEVELOPMENT OF A STOCKPILE HEATED AND AMBIENT AIR DRYER (SHAD) FOR FRESHLY HARVESTED ALMONDS

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Highlights

- Almonds are conventionally dried in windrows, a process that accumulates significant dust.
- Almonds were dried on-farm directly from the almond tree eliminating windrow drying.
- SHAD dryer uses a combination of heated and ambient air to dry almonds in a stockpile.
- The dryer has a SMER of 0.64, MER of 1.02, and COP of 1.33.

Abstract. *Dust generated by farming activities is a safety hazard to farmworkers and an environmental contaminant. During the almond (Prunus dulcis) harvest in California, dust is primarily generated by the mechanized movement of almonds from the bare soil of the orchard floor, where they are sun-dried, into trucks for transport to processing facilities. Off-ground dust-less harvesting will only be achieved when the almond industry adopts feasible mechanical drying methods. Therefore, a stockpile heated and ambient air dryer (SHAD) was developed to determine the feasibility of dehydrating almonds (Var. 'Monterey'). A stockpile containing 4,155 kg of almonds was created and almonds were dehydrated from their initial 12.6% almond kernel dry-basis moisture content (MC_{db}) to final MC_{db} of 6.04%. Drying was achieved as a combination of heated air at a temperature of 55^{o}C in the drying plenum with airflow of 0.078 m^3/s per m^3 of fresh almonds. After drying, almond quality parameters were measured, including damage by molds or decay, insect injury, and presence of internal cavities. Drying energy consumption, cost, and performance indicators were also determined. The differences in MC_{db} between the bottom, middle, and top layers of the almond stockpile were significant ($p \leq 0.05$). Post-hoc Tuckey test was conducted which indicated that the MC_{db} in the top layer was significantly lower than almond MC_{db} in the* *middle and bottom layers. Results showed that damage by molds or decay, insect injury, and internal cavities were 1.81%, 0%, and 1.77% respectively after drying. Therefore, the overall almond quality was not compromised. The drying process cost $ 11.65 per tonne of the initial weight of almonds with a Specific Moisture Extraction Rate (SMER) of 0.64, Moisture Extraction Rate (MER) of 1.02, and a Coefficient of Performance (COP) of 1.33. Comparison with other dryers in the literature shows that SMER and MER are within limits. However, a low COP was observed.*

Keywords. *Energy, stockpile drying, postharvest, tree nuts, dust.*

Almonds (*Prunus dulcis*) belong to the Rosaceae family, which includes many edible and economically important fruits such as peaches, raspberries, and apples (Potter et al., 2007; Verma, 2014). The almond fruit is a drupe that contains a thick fleshy exocarp, called the hull (Yetunde and Udofia, 2015). The hull encloses a hard shell (hardened endocarp) containing a seed, which is the edible component known as the kernel (Verma, 2014). Figures 1a, 1b, and 1c show the percentage mass (including moisture) of all the almond fruit components at harvest, an almond fruit illustration, and the estimated dry basis moisture content (MC_{db}) of different components of almonds at harvest, respectively. Average global almond production has increased by 26% over the past 10 years, reaching about 1.36 million tonnes during the 2019 season (INC, 2020). California is the leading world producer accounting for 77% of the world market share, followed by Australia and Spain with 8% and 6%, respectively (INC, 2020).

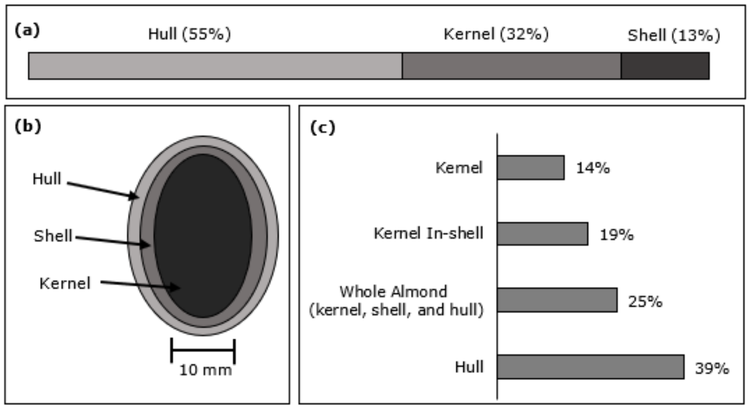
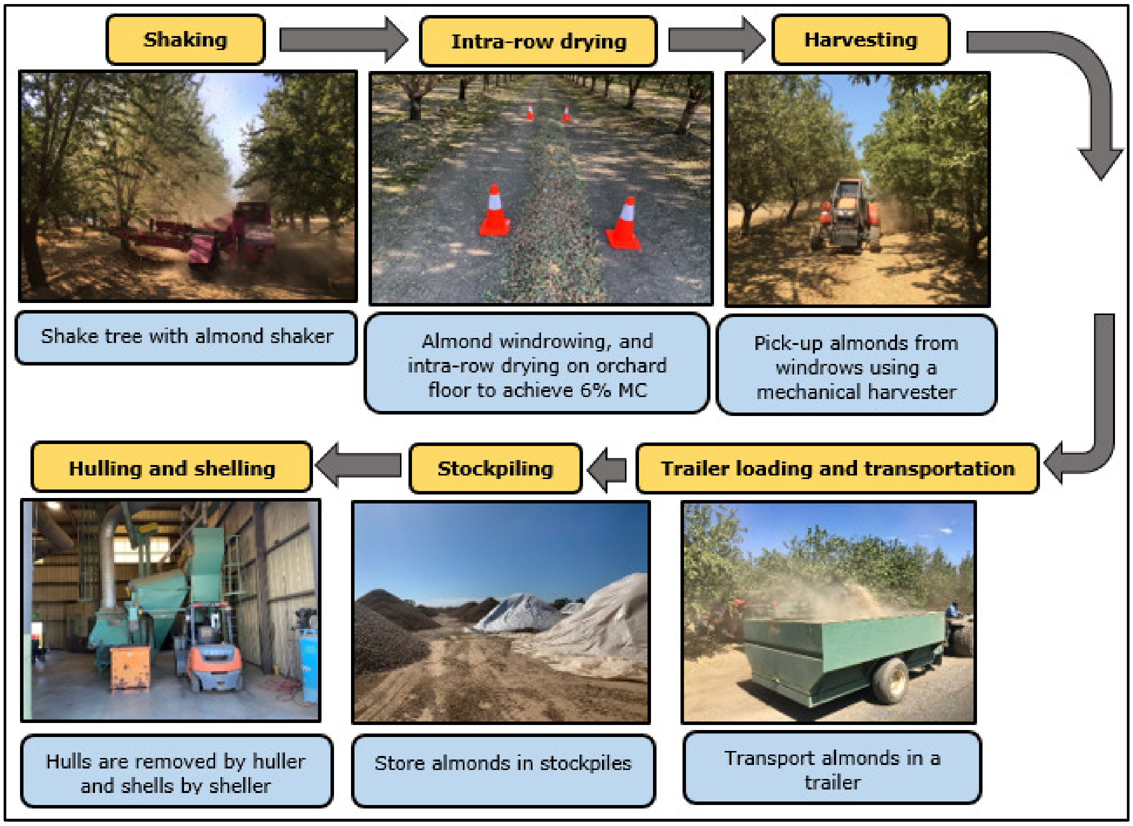


Figure 1 (a). Percentage mass (including moisture) of almond components at harvest; (b) Schematic representation of main components of almonds (Dingke and Fielke, 2014); and (c) Approximate dry basis moisture content (MC_{db}) of different almond components at harvest (Moreira and Bakker-Arkema, 1989). Typical dimensions of a whole almond at harvest: Length: 25.74 to 40.89 mm, Width: 16.13 to 29.20 mm, Thickness: 12.69 to 37.32 mm (Dingke and Fielke, 2014).

Currently, almonds are harvested by vigorously shaking the tree with a mechanical shaker to drop them on the ground. Harvesting of almonds is carried out when the fruit is nearing 100% hull split, exposing the almond shell within the hull (Connell, 1996). Almonds are then left to dry on the orchard floor for up to 21 days where they dry from a typical 10% to 20% kernel dry basis moisture content (MC_{db}) to an industry storage standard of about 6% MC_{db} or less. Drying is imperative as it increases almond shelf life and reduces their susceptibility to developing molds, rancidity (Chilka and Ranade, 2018; Perry et al., 2010), and concealed damage (Reil et al., 1996). The dried almonds are then swept into a central windrow, parallel to the almond tree rows by a large mechanical sweeper that uses a cylindrical sweeper head with rubber or metal tines and a blower that often generates significant dust (Faulkner and Capered, 2012). Almonds are then picked up from the windrows on the orchard floor by mechanical pickers with considerable dust and are transported to the hulling and shelling facility as described in Figure 2.

The pickup process generates dust as the pickup machine removes dirt, dust, leaf, and other trash from the windrow materials using a suction fan that discharges into the almond orchard (Downey et al., 2008). More specifically, CARB (2017) reported that shaking, sweeping and pickup of almonds from the ground accumulates nearly 14.15 kg (31.2 Ib) of microscopic dust particles (PM_{10}) when 4,047 m^2 (1 acre) of almonds is harvested, which translates to 16.7 million kg (37 million lb) of PM_{10}. Based on 2019 California acreage of approximately 4.8 billion m^2 or 1,180,000 acres (CDFA, 2020). In 2019, the Almond Board of California (ABC) set a goal to reduce 50% of dust accumulated during the almond harvest by 2025 (ABC,



2020). Reducing dust in the almond industry can range from addressing the steps that create most of the visible dust such as the sweeper and pick-up, all the way to dust-less (no soil contact) harvesting, challenging every step in the harvesting process. However, the lack of feasible mechanical drying methods impedes the voluntary adoption of practices that significantly reduce harvest dust. Additionally, the existing natural process of sun-drying almonds in the orchard is compromised if it rains or during periods of high humidity. The previous, calls for the need for a high-volume mechanical method of drying, which if appropriately developed, will potentially lead to overall improvements in efficiency and cost reduction within the almond industry.

Figure 2. Flow diagram showing post-harvest handling steps currently applied by almond growers in the USA.

The common practice during the almond harvest is to stockpile almonds in the open after drying. Moist almonds cannot be stockpiled since they are more susceptible to mold growth. Therefore, the objective of this study was to develop an outdoor stockpile heated and ambient air dryer (SHAD) to determine the feasibility of dehydrating almonds (Var. '*Monterey*') in a stockpile adjacent to a commercial almond orchard. To assess this concept, an almond stockpile containing an initial mass of 4,155 kg was built and dehydrated from its initial 12.6±1.6% almond kernel dry-basis moisture content (MC_{db}) to the desired storage conditions equal to or less than 6% MC_{db}. Kernel damage by molds or decay, insect injury, and the presence of internal cavities were the quality parameters tested for the freshly harvested and dried almond samples. Then the energy efficiency, energy cost, and dryer performance indicators of the stockpile dryer were calculated and compared with other dryers.

MATERIALS AND METHODS

SAMPLE PREPARATION

Fresh '*Monterey*' almonds were harvested from NICKELS Soil Laboratory (Arbuckle, California) nearing 100% hull split and swept into a windrow by a Flory Model 7630 sweeper (Flory Industries, Salida, CA). Almonds were picked up using a Flory 480 PTO harvester (Flory Industries, Salida, CA) powered by a Kubota M108 tractor (Kubota Tractor Co, Grapevine, Texas) and transferred to a conveyor cart (Jessee Manufacturing Co, Chico, CA). Immediately after pickup, experimental samples were collected from the conveyor cart using a plastic container, which carried about 2 kg (4.4 lb) of almonds, and they were placed in a labeled sample mesh bag. Almond collection was repeated to yield a total of 42 samples. Twelve samples were immediately transported to the Postharvest engineering laboratory at the University of California (UC) Davis (Davis, CA) to test for initial moisture content and quality parameters. A wireless data logger (El-USB-2, Lascar electronics Co, Erie, Pennsylvania, USA) that recorded temperature (T), relative humidity (RH), and dew point temperature every 5 minutes was placed in each of the remaining samples (30). These were used to monitor the drying process within the stockpile. Each data logger was roughly placed in the center of each sample mesh bag and fully covered with almonds to shield it from the environment.

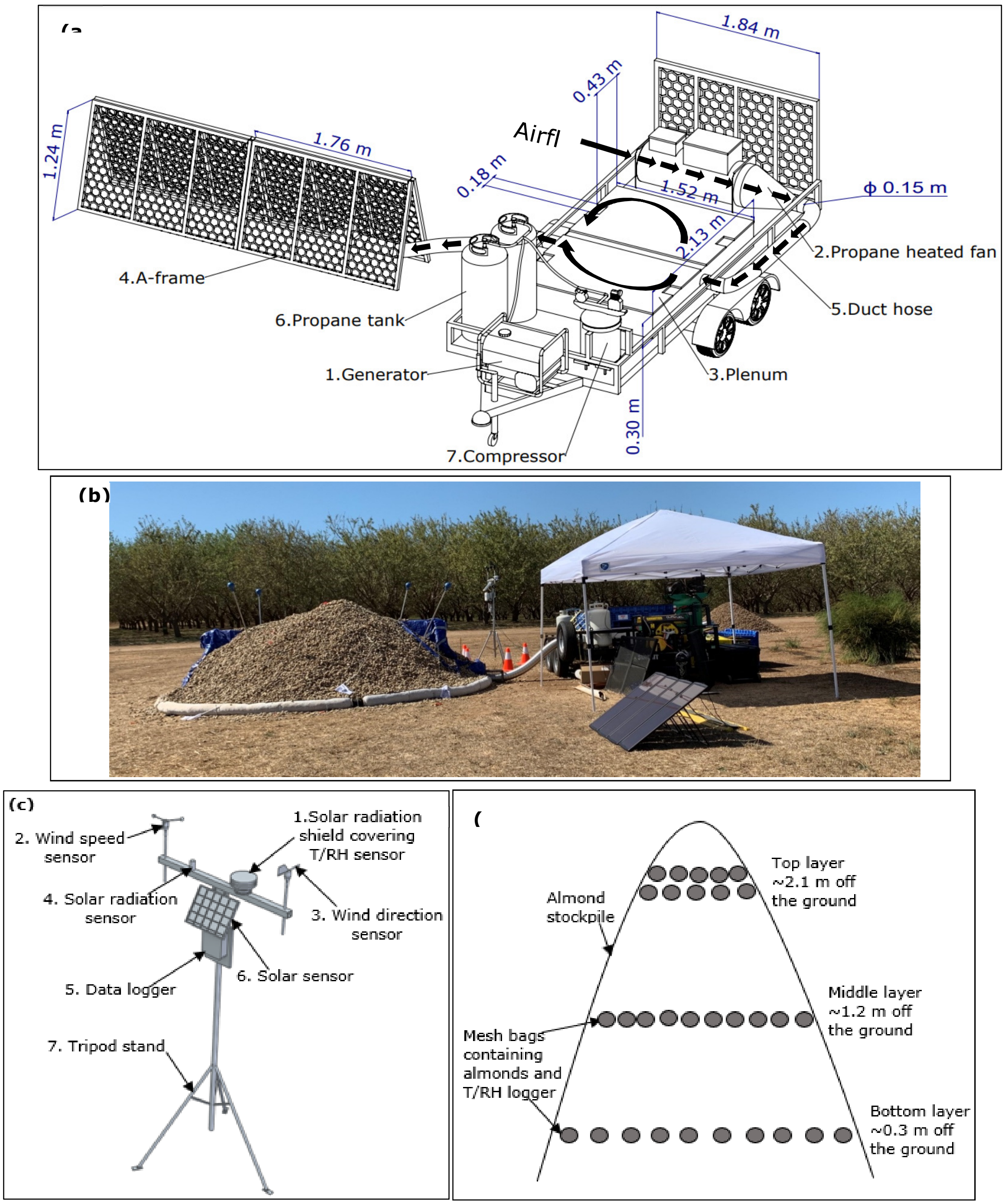


Figure 3 (a). Schematic representation of stockpile dryer showing main components. (b). Picture showing stockpile dryer, taken at NICKELS soil laboratory Orchards (Arbuckle, California). (c). Schematic representation of the weather station kit and the main components. (d) Schematic representation of stockpile of almonds showing three layers of almonds.

DRYING EQUIPMENT (PORTABLE INFIELD ALMOND DRYER)

A mobile stand-alone drying system used for the stockpile drying experiment was built at the Biological and Agricultural Engineering (BAE) fabrication shop at UC Davis (Figs.3a and 3b). The drying system consists of the following components: 1) A 7.25 kW (9.72 hp) dual powered (propane and gasoline) generator (Model 100297, Champion Global power equipment, Santa Fe Springs, California, USA); 2) A 1.49 kW (2 hp) propane heated vane axial fan with a 457.20 mm (18 in) diameter outlet (Sukup Manufacturing Co, Sheffield, Iowa, USA); 3) A 2.13 m (7 ft) x 1.52 m (5 ft) x 0.30 m (1 ft) air distribution plenum built from 28.70 mm (1.13 in) thickness plywood; 4) A 1.22 m (4 ft) height x 1.83 m (6-ft) carbon steel diamond-shaped expanded metal A-frame with 3.05 mm (0.12 in) overall thickness, openings of 42.93 mm (1.69 in) x 14.22 mm (0.56 in), strand thickness of 4.06 mm(0.16 in) and strand width of 3.05 mm (0.12 in); 5) High temperature rigid 304 stainless steel duct hoses of 152.40 mm (6 in) diameter to connect the fan to the plenum, and the plenum to the A-frame. A pressure sensor (Series MS Magnesense, Dwyer Instruments Inc, Michigan City, Indiana, USA) was used to record pressure in the drying plenum.

A rechargeable battery operated weather station (Fig 3c) with a 5 W solar panel, held by a 2.99 m (9.8 ft) tripod (U30-NRC-SYS-C, Onset Computer Corp, Bourne, Massachusetts, USA) was placed adjacent to the drying system to monitor environmental conditions during the experiment, consisting of the following: 1) A T/RH sensor (S-THB-M002, Onset Computer Corp) covered by a solar radiation shield (RS3, Onset Computer Corp); 2) A wind speed sensor (S-WSB-M003, Onset Computer Corp); 3) A wind direction sensor (S-WDA-M003); 4) A solar radiation sensor (S-LIB-M003); 5) A data logger (HOBO U30 NRC, Onset Computer Corp) to store the data from the weather station sensors at 5-minute intervals.

DRYING STOCKPILE AND SAMPLE DISTRIBUTION

Almonds were deposited directly from the conveyer cart onto the A-frame until a stockpile height of about 0.30 m (1.00 ft) was achieved to form the bottom layer, ten replicates of almond mesh bags containing T/RH sensors were placed on the partial almond stockpile. The procedure was repeated to form the middle and top layers, with a partial stockpile height of 1.22 m (4.00 ft), and 2.13 m (7.00 ft) respectively, as shown in Figure 3d. The conveyer cart contained an inbuilt weighing scale that was used to record the almond stockpile mass that amounted to 4,155 kg (9,160 lb) at a height, width, and length equal to 2.13 m (7.00 ft) x 3.05 m (10.00 ft) x 3.66 m (12.00 ft) respectively. Corrugated French pipes of size 0.09 m (0.30 ft) x 3.05 m (10.00 ft) were used to demarcate the stockpile perimeter and keep it intact. Almonds were dried for 11 days until the desired storage moisture content of about 6% MC_{db} was achieved (USDA, 2019).

Drying was achieved as a combination of heated air at 55 ± 5.29ºC (131 ± 41 .52ºF) recorded in the drying plenum with airflow of 0.078 ± 0.02 m^3/s per m^3 of fresh almonds (4.69 ± 1.13 cfm/ft^3 of fresh almonds), and ambient air at a temperature and relative humidity of 18.47 ± 5.43ºC (65.25 ± 41.77ºF) and 31.74 ± 13.77% respectively. After drying, 30 mesh bag samples of almonds were retrieved from the stockpile and immediately transported to the Postharvest engineering laboratory at UC Davis to test for final moisture content and quality parameters.

SAMPLE MOISTURE CONTENT DETERMINATION

Five almonds were randomly selected from each sample mesh bag. Hulls were manually removed (hulling), and then kernels were extracted after the shell was cracked with a hammer (shelling). Almond kernels were then placed in a 70 mm (2.8 in) diameter aluminum crimpled-walled weighing dish (Cole-Parmer instrument co, Vernon Hills, Illinois, USA). Dry basis moisture content (MD_{db}), expressed as a percentage, was determined using the oven drying method for 24 hours at an oven temperature of 105ºC as described by AOAC, (1990).

QUALITY PARAMETERS

Ten almonds were randomly selected from each sample mesh bag to visually quantify any damage by molds or decay, insect injury, and presence of internal cavities. The number of defective almonds was counted and expressed as a percentage of the total sample (10) per tested quality parameter, as specified in the shipping point and market inspection instructions almonds manual (USDA, 1998). The presence of split cotyledons after cutting the kernels in half with a knife shows internal cavities (Coates, 2018). Moldy almonds were denoted when visible on the kernel. The white or grey mold that could easily be rubbed off with fingers was ignored and decay was recorded when the kernel was completely or partially decomposed (USDA, 1998; Kader, 2013). The presence of insect, web, frass, or evidence of insect feeding was counted as insect injury (Schatzki and Ong, 2001; USDA, 1998).

ENERGY USAGE DURING DRYING

The total energy utilized by the SHAD is the sum of the electrical and propane energy consumed by the heater and fan. Electrical usage (E_1) expressed in kWh is computed using Equation 1 (Motevali et al., 2011; Muralidhara, 2017).

$$E_1 = dp \times q \times t \tag{1}$$

where

dp is the total pressure within the plenum (Pa).

q is the fan-delivered airflow (m^3/s), which was calculated from the fan performance curve.

t is the drying time (h)

Propane energy usage (E_2) by the heated fan is computed using Equation 2

$$E_2 = N \times P \tag{2}$$

where

N is the amount of propane used by the heater (L).

P is the amount of energy in 1 liter of propane gas, equal to 25,503 kJ (Elgas, 2019)

The total energy used E_t (kJ) is given by Equation 3, after converting E_1 from kWh to kJ, where 1 kWh is equal to 3,600 kJ.

$$E_t = E_1 + E_2 \quad (3)$$

where

E_t is the total energy consumption.

Specific energy required to removed 1000 kg (a tonne) of water from the almond stockpile (E_{tn}) is calculated using Equation 4.

$$E_{tn} = \frac{E_t}{w} \times 1000 \quad (5)$$

where

W is the mass of water removed from the almonds (271 kg),

Factor *1000* denotes a tonne of water in the almonds.

ENERGY COST

The energy cost required to dry a tonne of the initial weight of almond stockpile (C_{tn}) is calculated using Equation 5.

$$C_{tn} = \frac{C_t}{m_a} \times 1000 \quad (5)$$

where

C_t is the sum of the propane cost (Cp) and electricity cost (Ce).

Cp is the total propane cost ($ 0.63 per liter of propane) (EIA, 2019)

Ce is the total electricity cost ($ 0.16 per 1 kWh) (EIA, 2020).

m_a is the initial weight of almonds (4,155 kg)

Factor *1000* denotes a tonne of almonds before drying.

Dryer performance Indicators

Specific Moisture Extraction Rate (SMER)

SMER (kg/kWh) describes the effectiveness of energy used in the drying process (Prasertsan and Saensaby, 1998), calculated using Equation 6 (Stawreberg & Nilsson, 2010, Liu et al., 2018).

$$SMER = \frac{W}{E_t} \quad (6)$$

Moisture Extraction Rate (MER)

MER (kg/h) measures the dryer capacity (Prasertsan and Saen-saby, 1998), calculated using Equation 7 (Liu et al., 2018).

$$MER = \frac{W}{t} \quad (7)$$

Coefficient of Performance (COP)

COP is used to evaluate the efficiency of the propane heated fan. COP is a dimensionless value expressed as the ratio of energy produced to the energy used by the propane heated fan, calculated using Equation 8 (Oktay and Hepbasli, 2003; Yahya, 2016)

$$COP = \frac{\sum Q}{E_T} \quad (8)$$

where

$\sum Q$ (kJ) is the total dissipated energy.

Ruíz (2015) indicates that *Q* is calculated as the sum of the energy required to raise the temperature of the almonds and the latent heat used to remove water from the almonds, as shown in Equation 9.

$$Q = m_a \times C_a(T_1 - T_2) + W \times C_v \quad (9)$$

where

C_a is the specific heat capacity of the almonds taken as 2.2 kJ/kgK (ASHRAE,2010)

T_1 and T_2 are the initial and final temperatures of the almonds.

During drying, the heater automatically turned on and off, controlling the airflow, pressure buildup, and saving energy usage. Equation 9 was modified into Equation 10 to account for the total energy ($\sum Q$)

required to raise the temperature of the almonds during drying, as quantified by temperature sensors in each almond sample.

$$\sum Q = m_a \times C_a \times \sum(T_1 - T_2) + W \times C_v \quad (10)$$

where

$\sum(T_1 - T_2)$ is the summation of temperature rises during the entire drying period.

Latent heat of vaporization of water (C_v) at 55 ºC is 2,369.63 KJ/Kg (Osborne et al., 1939)

2.7 Data Analysis

All data visualization and analysis were developed in SAS Enterprise 7.1. A split-plot design was used for this experiment, where the stockpile (plot) was partitioned into three subplots: bottom, middle and top layers. Analysis-of-Variance (ANOVA) was conducted on both moisture content and quality parameters to determine whether the differences were statistically significant at each height level. When a significant main effect was found, a post-hoc test using Tukey's Honest Significant Difference (HSD) test was conducted to ascertain where the difference of the means lies in the height levels at a 95% confidence level ($p \leq 0.05$). To assess this, data of temperature and relative humidity (RH) within each mesh bag sample were graphed against time (days) for each stockpile level (bottom, middle, and top) to visualize their trend and relationship.

RESULTS AND DISCUSSION

Moisture content and quality parameters

After 11 days of drying, the mean MC_{db} for the bottom, middle and top layers were 7.12 ± 2.64%, 6.42 ± 3.27%, 4.59 ± 0.73% respectively as shown in Figure 4a. ANOVA test showed that MC_{db} was significantly different between the stockpile layers (p-value < 0.01, F-value = 8.67, 2 degrees-of-freedom). Post hoc Tukey's honestly significant difference (HSD) test was conducted, which showed that the MC_{db} in the bottom and middle layers were not statistically different. It is hypothesized that the significant difference between the MC_{db} in the stockpile layers can partly be attributed to the non-uniform distribution of air during the drying process.

Quality parameter testing for almonds before drying showed that internal cavities, decay or mold damage, and insect injury were 0%. After drying, the almond stockpile was 96.12 ± 3.59% free from quality concerns or defects. Internal cavities and decay or mold damage contributed 1.77 ± 2.66%, and 1.81 ± 2.57%, respectively (Fig 4b). No evidence of insect injury was observed, so this factor was excluded for further analysis. ANOVA showed that the differences of the quality parameters were not significant between the stockpile layers (p-value = 0.93, F-value = 0.26, 5 degrees-of-freedom), therefore a post hoc test was not conducted. Mold or decay can potentially be attributed to sections within the stockpile, which did not receive sufficient air due to the potential lack of proper air distributed through the stockpile. Coates (2018) indicated that internal cavities are caused by a fast-drying rate, where the outer surface of the almond solidifies before the center leading to kernel splitting. USDA (1998) reports that decay or mold damage and insect injury have a 5% tolerance during grading while live insects have 0% tolerance, hence the quality parameter results are low and not concerning.

AMBIENT CONDITIONS

The stockpile was assumed to receive the same treatment of ambient conditions throughout, which are as follows: Average ambient temperature of 18.47 ± 5.43^{o}C (65.25 ± 41.77^{o}F) and RH of 31.74 ± 13.77% recorded by T/RH sensor; average wind speed of 1.61 ± 2.03 m/s and gust speed of 2.78 ± 2.81 m/s recorded by wind speed sensor; average wind direction of 133.30 ± 65.42 ∅ recorded by wind direction sensor; and average solar radiation of 197.47 ± 262.19 W/m^2 recorded by a solar radiation sensor.

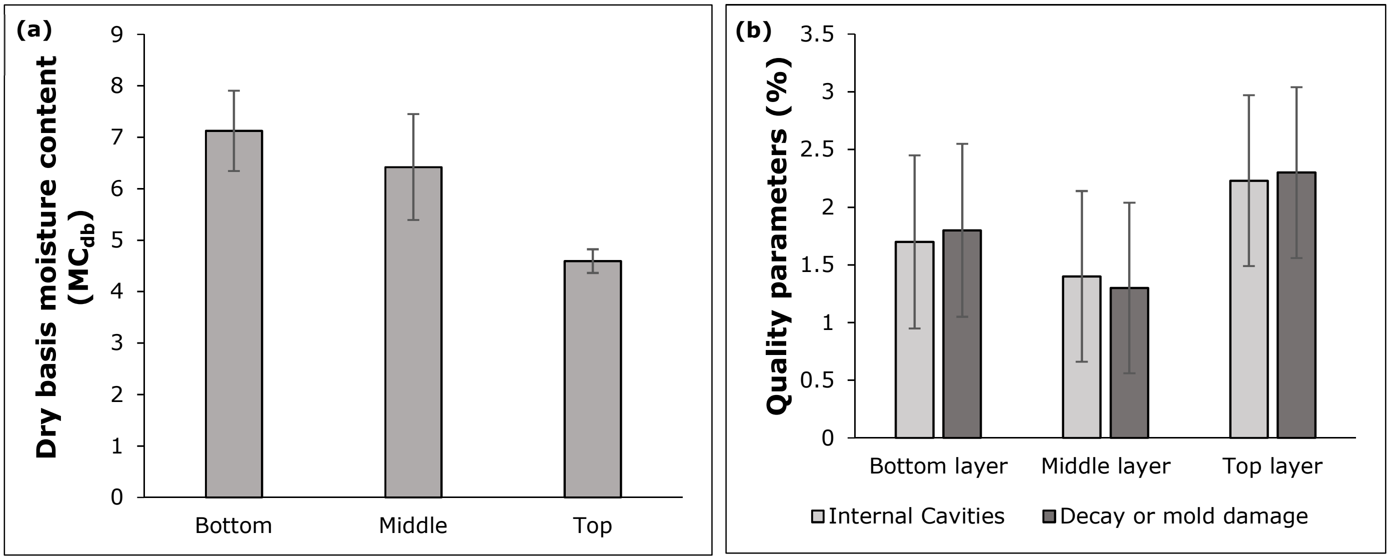


Figure 4. (a) Bar plot showing moisture content with stockpile layer. Bar plots followed by the same letter are not significantly different at p = 0.05 (ANOVA) (Tukey's Honest Significant Difference). (b) Bar plots showing quality parameters (%) per stockpile layer. Error bars indicate standard error.

DRYING CONDITIONS

Freshly harvested almonds with an initial kernel MC_{db} of 12.6±1.6% and the initial RH for the almond stockpile was 70.38 ± 2.87%. At the end of the drying period, the top layer yielded the lowest RH (26.25%) in comparison to the middle (52.95%) and bottom layers (58.40%) as shown in Figure 5a. Additionally, a low rate of change in RH was recorded for the bottom (0.58% per day) and middle layers (0.26% per day) of the stockpile, which was not the case for the top layer (5.91% per day). Differences in RH can be partly attributed to the differences in the distribution and air delivery from the fan. Figure 5b shows the temperature profile. The fan ran throughout the entire experiment, but the heater turned on and off depending on the ambient conditions accounting for 28% of the drying time. The large temperature gap between the plenum temperature when the heater was on and the temperature of the almonds is an indication that the system was not efficient in achieving the desired drying temperature.

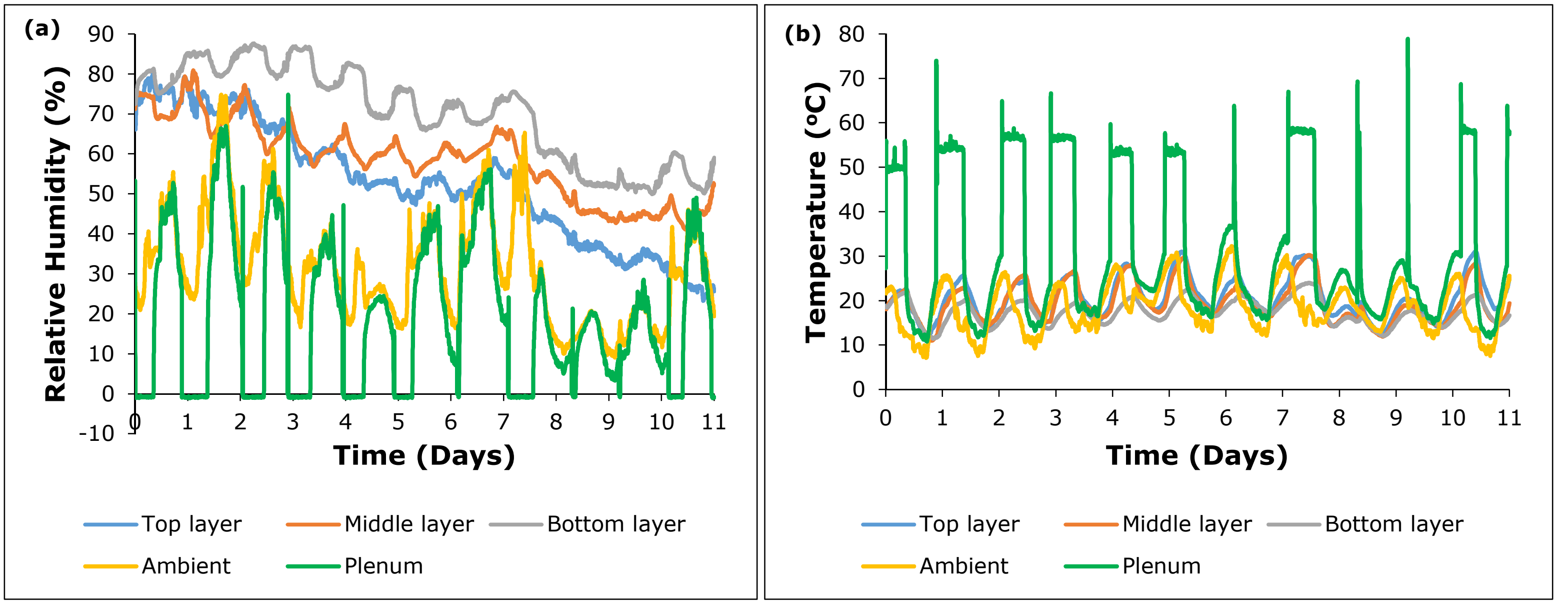


Figure 5. (a). Relative Humidity profile. (b) Temperature profile

ENERGY USAGE DURING DRYING

An average pressure (*dp*) of 308.48 ± 74.1 Pa and airflow (*q*) of 1.86 ± 0.45 m^3/s (3941.12 ± 953.5 cfm) were recorded in the drying plenum. Electrical energy consumption equaled 545,328 kJ, propane energy usage equaled 978,809.36 kJ, and therefore the total energy consumption during the whole drying process was 1,524,137.36 kJ. The energy required to remove a tonne of water from the almond stockpile (E_{tn}) is 5,623,290 kJ/kg of water.

ENERGY COST

Propane and electricity costs of $ 24.18 and $ 24.24 respectively were calculated, achieving a total drying cost of $ 48.42. The cost required to dry a tonne of almonds is $ 11.65.

DRYER PERFORMANCE INDICATORS

Drying in this experiment was achieved as a combination of using both heated and ambient air to attain a SMER, MER, and COP of 0.64 kg/kWh, 1.02 kg/h, and 1.33 respectively. Perera and Rahman (1997), indicated that SMER of Heated Air Dryers (HAD) is in the 0.12 – 1.28 range. Further, Pal and Khan (2010) reported that drying sweet pepper with a HAD at 45° C (113° F) yielded a SMER of 0.93 kg/kWh and

MER of 0.22 kg/h, increasing the drying temperature to 55° C (131° F) provided SMER of 1.06 kg/kWh and MER of 0.37 kg/h. Therefore, the SMER of SHAD is within the range of existing HAD, and MER higher than the reported study was recorded.

A comparison of SHAD used in the experiment with other types of dryers shows that SMER (Fig 6a) and MER (Fig 6b) values are within the appropriate range. However, comparisons show that a low COP (Fig 6c) was generated. Kitanovski et al. (2009) reported that a low COP means the system was not efficient. For the case of SHAD, non-uniform distribution of warm air in the stockpile and heat lost because some sections of the A-frame were not fully covered by the almond stockpile which in turn forces longer drying periods are partly contributed to a low COP.

Ultimately, further studies will focus on improving air distribution within the stockpile during the drying process, this can be achieved by introducing an air distribution duct underneath the stockpile with channels diverting air to the entire stockpile. The concept is adapted from Das et al. (2001) where an air distribution duct was developed for an air recirculating tray dryer and Noyes (2006) suggested the use of multiple air ducts to distribute the air in silos. Also, further studies comparing the SHAD with the conventional windrow drying method need to be carried out in parallel. Altering the drying conditions, such as drying temperature and airflow will also be considered.

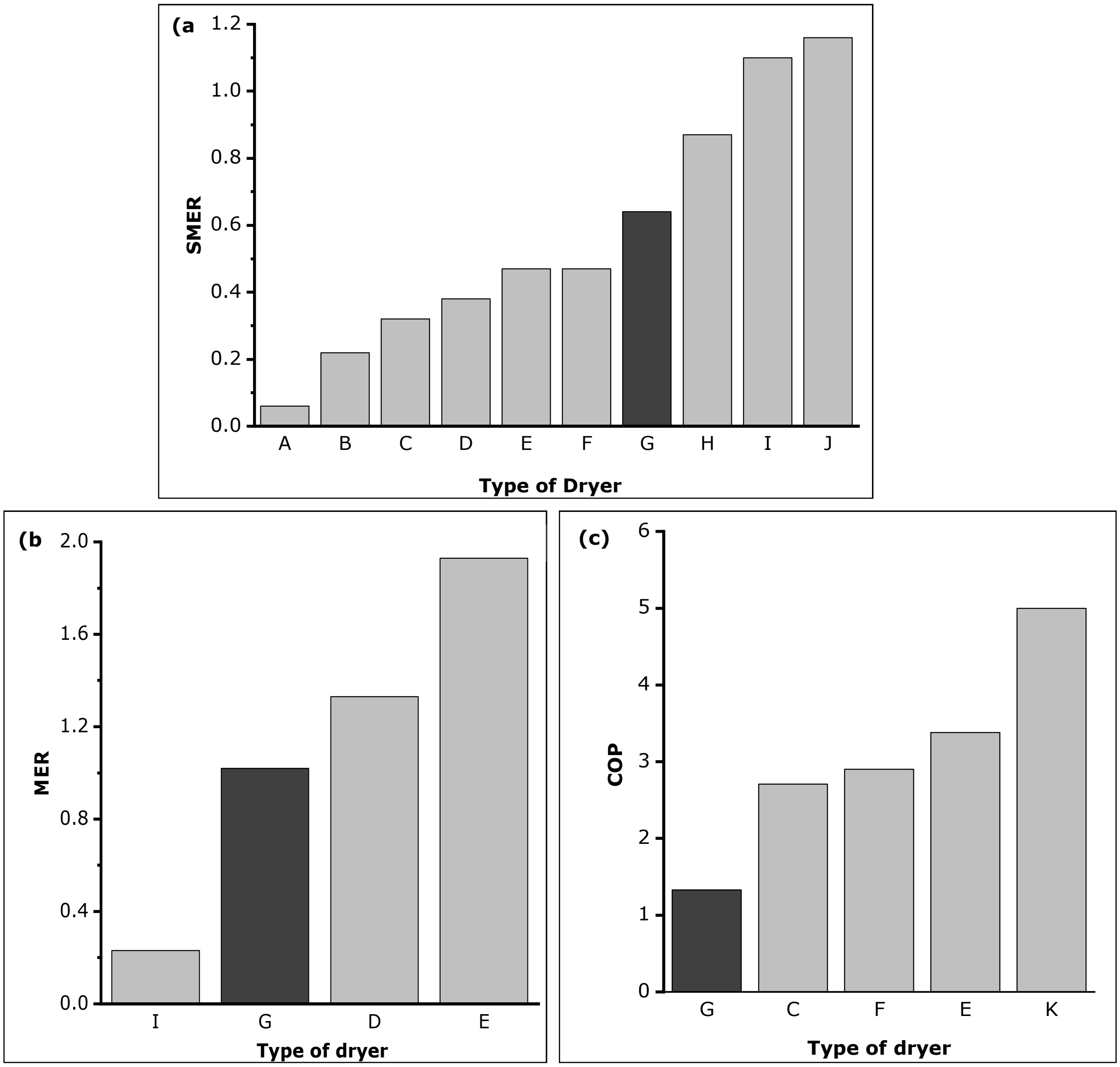


Figure 6. (a). Bar plot comparing SMER of different dryers. (b) Bar plot comparing MER of different dryers. (c) Bar plot comparing COP of different dryers. A- Closed system heat pump dryer for ginger at 50 ºC (Chapchaimoh et al., 2016), B- Convection solar dryer for bitter gourd (Vijayan et al., 2016), C- Heat pump dryer for tomato slices at 45 ºC (Coşkun et al., 2017), D- Solar dryer for cassava at 40 ºC (Yahya et al., 2016), E- Solar assisted heat pump dryer for cassava at 45 ºC (Yahya et al., 2016), F-Solar assisted heat pump for mushrooms at 45 ºC (Şevik et al., 2013), G-Stockpile heated and ambient air dryer for almonds at 55 ºC (this study), H- Solar dryer for chili at 50 ºC (Mohanraj and Chandrasekar, 2009), I-Heat pump dryer for sweet pepper at 40 ºC (Pal & Khan, 2010). J- Heat pump assisted hybrid photovoltaic thermal solar dryer for saffron at 45 ºC (Mortezapour et al., 2012). K – Heat pump for Mint leaves at 45 ºC (Ceylan & Gürel, 2006)

CONCLUSION

SHAD was developed to directly dry almonds outdoor in stockpiles. SHAD is intended to replace the conventional windrow drying of almonds, which involves sweeping and picking processes that accumulate dust. The adaptation of the SHAD has the potential to reduce the drying time of almonds if the efficiency of the dryer is improved. Almond stockpile of 4,155 kg was dried with SHAD using a combination of heated and ambient air for 11 days. Almonds were dried from 12.6 ± 1.6% to 6.046 ± 2.63 MC_{db}, Tukey's HSD test showed that the bottom (7.125 ± 2.462 MC_{db}) and the middle layer (6.421 ± 3.265 MC_{db}) were in the same Tukey grouping from the top layer (4.593 ± 0.734 MC_{db}). This is attributed to the non-uniform distribution of air within the stockpile and air leakages which led to warm air escaping rather than going through the stockpile.

Initial quality parameter tests showed that internal cavities, decay or mold damage, and insect injury were 0%. After drying, the stockpile was tested to be 96.12 ± 3.59% free from quality concerns, attributed to 1.77 ± 2.66% internal cavities, 1.81 ± 2.57% decay or mold damage, and there was no insect injury. The effect of quality parameters on the stockpile layer was found not to be significant ($p < 0.05$). Energy performance tests showed a SMER of 0.64 kg/kWh, MER of 1.02 kg/h, COP of 1.33, and the drying process cost $11.65 per tonne. Comparison with other commercial dryers showed that SMER and MER are within acceptable limits, however, a low COP was observed.

The major drawback is that there was lack of appropriate air distribution through the stockpile. Work is ongoing to develop an air distributor to be placed underneath the A-frame to ensure that drying air is evenly distributed throughout the stockpile. Further studies will also include a parallel comparison of the SHAD drying method with the conventional windrow drying of almonds.

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