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FINAL PROJECT REPORT

Demonstration and Commercial Implementation of Energy-Efficient Drying for Walnuts

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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division manages the Gas Research and Development Program, which supports energy-related research, development, and demonstration not adequately provided by competitive and regulated markets. These natural gas research investments spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

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- Buildings End-Use Energy Efficiency
- Industrial, Agriculture and Water Efficiency
- Renewable Energy and Advanced Generation
- Natural Gas Infrastructure Safety and Integrity
- Energy-Related Environmental Research
- Natural Gas-Related Transportation

Demonstration and Commercial Implementation of Energy-Efficient Drying for Walnuts is the final report for the Demonstration and Commercial Implementation of Energy-Efficient Drying for Walnuts project (contract number PIR-13-010) conducted by University of California, Davis. The information from this project contributes to the Energy Research and Development Division's Industrial/Agricultural/Water End-Use Energy Efficiency Program.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the Energy Research and Development Division at ERDD@energy.ca.gov.

ABSTRACT

An energy efficient drying system for walnuts using infrared (IR) as the heating source was demonstrated to reduce drying times and energy use in walnut drying. A pilot scale infrared walnut dryer with a capacity of 1 ton per hour was built in collaboration with Wizard Manufacturing Inc., and tested at Emerald Farms, Maxwell, California, in 2015. The drying test was performed after sorting the walnuts into two moisture groups of low- and high-moisture walnuts. The high moisture walnuts were pre-dried in the IR walnut dryer by heating the walnuts to the kernel temperature of 104-122°F (40-50°C) in the pilot-scale IR dryer. The IR pre-dried walnuts were conveyed to the hot-air drying bins and dried using hot air at 109°F (43°C) to a moisture content of 8 percent. The nearby hot-air drying bins were filled with walnuts without IR pre-drying and dried to 8 percent MC for comparison. The IR-preheated walnuts were dried faster and saved about 12 percent of energy used for drying.

A commercial scale IR walnut dryer with a capacity of 10-15 tons per hour (tph) was designed, built, tested and demonstrated. IR pre-drying of walnuts for 4 minutes prior to hot-air drying reduced the hot-air drying time by 13.6 percent to 26.5 percent when compared with walnuts that were not heated by IR and saved 9.96 percent to 19.94 percent of energy used in walnut drying. The IR pre-dried walnuts had the better quality and longer shelf life as those of walnuts dried by hot air alone.

Keywords: walnut, Infrared heating, energy saving, drying time reduction, quality, shelf life

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Introduction

Walnuts are an important California agricultural crop, producing 686,000 tons of nuts and contributing $1.24 billion to the state's economy. California has about 5,000 growers and 63 processors and produces 99 percent of the U.S. walnut production. After harvesting, walnuts must be dried quickly to avoid quality loss and food safety problems. Walnut drying is one of the most expensive processes, taking more than 24 hours by hot air drying and consuming an average of 12 therms of natural gas and 24 kWh of electricity to dry one ton of walnuts.

Currently used walnut drying method commingles all nuts from the field, which are cleaned, washed and conveyed to drying bins. Hot air at 109.4°F (43°C) is used to dry walnuts to a safe moisture content level of 8 percent. This current drying practice has a few major challenges including drying walnuts with various moisture contents at harvest, resulting in over-drying and under-drying the nuts; and over-drying and under-drying simultaneously, which leads to poor product quality and a waste of energy. The walnuts, on average, pick up about 4-percent moisture when they are washed. These walnuts are normally kept in drying bins for 2-3 hours before drying so that during this time water soaks into the walnut shells, resulting in an additional 4-6 hours of drying. Walnut growers are therefore looking for a drying technology that significantly reduces drying times and energy use, allowing them to both produce high-quality walnuts and reduce processing costs.

Project Purpose

This project successfully demonstrated a cost-effective and energy efficient walnut-drying method to produce walnuts with high-quality and longer shelf life. This project showed that drying time and energy in walnut drying could be saved by separating or sorting the hulled walnuts into two moisture groups before drying and pre-drying them using catalytic infrared emitters to quickly remove surface moisture. Sorting walnuts and infrared (IR) pre-drying also improved the quality of the nuts by reducing over-drying and under-drying. Infrared energy is a form of electromagnetic waves, or electromagnetic radiation. This technology addressed the challenges of energy consumption from low-efficiency hot-air drying, and demonstrated a new energy-efficient drying technology that reduces both drying times and production costs. The project team:

- Designed and built a commercial IR drying system for walnuts, optimizing the operation parameters of the commercial system.
- Quantified the energy savings and walnut quality improvement by using an IR drying system.
- Demonstrated and disseminated the new energy-efficient drying technology to both walnut growers and processors.

The team documented the benefits and viability of the new drying technology for walnuts on a commercial scale for energy savings and environmental pollution reductions while producing high-quality walnuts with longer shelf life than existing drying methods.

Project Results

The team successfully demonstrated a pilot scale (1 ton per hour [tph]) and a commercial scale IR dryer (15 tph) to reduce walnut drying time and energy saving to produce high-quality walnuts with longer shelf lives when compared to the existing hot air walnut drying method. Drying tests were done by using the pilot scale IR dryer by pre-drying the walnuts to three different kernel temperatures of 104°F (40°C), 113°F (45°C), and 122°F (50°C), and then drying walnuts in the hot-air drying bins to a moisture content of 8 percent. The energy savings from IR pre–drying were 11.68 percent to 12.81 percent and energy savings by sorting into two moisture groups were 28.80 percent.

Based on the tests with the pilot scale IR dryer, a commercial scale IR walnut dryer with a capacity of 10-15 tph was designed, built, tested, and demonstrated. The tests of the commercial scale dryer showed that throughput capacity of the IR dryer was between 10.67 to 14.22 tph. IR pre-drying resulted in moisture removal of 3.1 percent to 5.2 percent, depending on the initial moisture content and IR heating time. IR pre-drying of walnuts reduced hot-air drying times by more than 13.5 percent to 26.5 percent when compared to hot-air drying of walnuts without IR pre-drying and resulted in the energy savings of almost 10 percent to 20 percent compared to walnuts dried without IR pre-drying.

Technology/Knowledge Transfer

The team successfully demonstrated a pilot scale (1 tph) and a commercial scale IR dryer (15 tph) to reduce drying time and increase energy savings in walnut drying. This process also produced high-quality walnuts with longer shelf life compared to the existing hot-air walnut drying method. Results showed drying time savings of up to 25 percent with IR pre-drying, increasing existing capacity by 25 percent. The walnuts can be harvested on time at maturity, instead of waiting for dryer availability (currently practiced by growers). Harvesting the walnuts at the right time at correct maturity and using quick drying can prevent quality loss (1-2 percent) and increase profits by $12-$14 million per year.

Walnut drying requires, on average, 12 therms of natural gas (or 13 gallons of propane), and 24 kWh of electricity per ton of dried nuts; inefficient operations may use twice as much. The energy savings of 25 percent will reduce the annual natural gas consumption by 2-million therms, a savings of $1.92 million per year. The electricity consumption will reduce by about 4-million kWh per year, resulting in savings of $1.2 million per year. Total benefits from sorting and IR pre-drying will be about $17-$19 million per year (including profits from quality loss and energy savings). The new walnut drying technology has been demonstrated to walnut growers and walnut processors, who acknowledged the drying-time reductions and energy savings during the demonstration.

CHAPTER 1: Design and Fabrication of the Infrared Walnut Pre-Drying System

Introduction

Walnuts are an important crop, contributing $1.24 billion to California's economy in 2016 with an annual production of 686 thousand tons. The walnut drying process, the most energy intensive step, is one of the largest consumers of natural gas and electricity. Even though the processors have attempted different approaches to reduce energy consumption for walnut drying, the average energy consumption is still high. The average energy consumption for walnut drying is 12.16 therms of natural gas or propane and 23.6 kWh electricity per ton of walnuts. Also, walnut drying is often a major bottleneck in walnut harvesting and processing as drying a batch of walnuts takes as long as 24 hours due to a low recommended maximum drying air temperature of 110°F (43.3°C). This drying air temperature limit was established in 1924 (Batchelor, 1924) during the introduction of heated air drying, which demonstrated that long-term exposure to temperatures higher than 110°F caused walnuts to become rancid during storage.

Currently used walnut drying methods commingle all nuts from the field, which are cleaned, washed, and conveyed to drying bins. Hot air at 109°F (43°C) is used to dry walnuts to a safe moisture content (MC) level of 8 percent on wet basis. The current drying practice has four major problems:

(1) Drying walnuts with huge variability in moisture contents of individual nuts at harvest results in both over-drying and under-drying walnuts.

(2) The over-drying and under-drying occur at the same time, which leads to poor product quality and a waste of energy.

(3) The walnuts pick up about 4 percent moisture on average when they are washed.

(4) These walnuts are normally kept in drying bins for 2-3 hours prior to drying. During this period, the water soaks into the walnut shells, resulting in an additional 4-6 hours of drying.

Therefore, walnut growers are looking for a drying technology to significantly reduce the drying time and energy usage required to produce high-quality walnuts. This drying technology first separated the walnuts (based on their moisture contents) using an air knife, then drying them with infrared (IR) heating during conveying before the walnuts reach the drying bins to be further dried with hot air.

In the last several years, the research team conducted comprehensive tests to develop energy-efficient drying technology using IR heating and separation based on their MCs before drying. They have proven the technical feasibility of using IR drying as an energy-efficient drying technology for walnuts. These results showed a huge variability in MC among individual walnuts at harvest; the walnuts with hulls had an average MC of 32.99 percent compared with

13.86 percent for walnuts without hulls. The shell MC was higher than the kernel MC. In fact, the average differences in MC between shell and kernel were 11.56 percent for walnuts with hulls and 6.45 percent for nuts without hulls. After hull removal and washing, the pneumatic method based on terminal velocity can be used to sort and separate walnuts into different groups with desired moisture ranges.

This concept was successfully tested at Emerald Farms in Maxwell, California. The results showed that savings in natural gas and electricity were achieved by the reduced drying time since over-drying was minimized. The previous study also showed that IR heating quickly removed the walnuts' shells and surface moisture without negatively affecting the quality of the dried walnuts. IR radiation is energy in the form of electromagnetic waves or electromagnetic radiation and can be used for thermal processing of food. Radiation heat first impinges on the surface of the material and then penetrates to the inside. It can be transferred from the heating element to the product surface without heating the surrounding air, so the energy transfer is highly efficient (Jones, 1992). Radiation heat transfer can occur between two bodies separated by a medium colder than both bodies (Cengal, 1998). The wavelength of IR falls in the spectrum of 0.76 to 1000 micrometers (μm) and can typically be categorized into near infrared (NIR) (0.76-2μm), medium infrared (MIR) (2-4 μm), and far infrared (FIR) (4-1000 μm). For agricultural food product processing, high temperatures corresponding to NIR radiation could cause product discoloration and quality deterioration; temperatures therefore need to be controlled if NIR is used. The FIR is associated with low temperatures and energy emissions. If the temperature is too low, the energy emitted may not be enough to meet the energy requirements in food processing. Useful temperatures of IR emission may be in the range of 302°F - 3992°F (150°C - 2200°C), which corresponds to the IR peak wavelengths of 7-1.2 μm.

Both absorptivity and penetration capability (transmissivity) of IR may vary with wavelengths of radiation and the physical and chemical characteristics of the food product being treated. Matching the peak power region of the radiation source with maximum radiation absorption points of the wet materials could be important for achieving rapid heating in the selection of IR emitters. Infrared radiation energy can be generated with various types of emitters such as catalytic emitters, electric emitters, carbon emitters, and ceramic emitters by converting fossil fuels (such as natural gas) or electric energy into radiation energy. The electric- and gas-fired MIR and FIR emitters have similar efficiencies (Johannes and Thijssen, 1997).

The IR drying technology uses infrared as an efficient heating source to quickly remove the surface and shell moisture of walnuts first, followed by the final drying, using hot air. Besides the high drying rates and energy savings accomplished by IR drying, improvement in the product quality was also achieved. The IR emitters used are catalytic infrared emitters. The principle of infrared energy generation from catalytic infrared emitters is via chemical reaction using catalysts, without any combustion. Compared to the combustion in burners used in current drying methods, the catalytic chemical reaction of IR emitters do not produce any NOx or greenhouse gases, making it environmentally friendly and important in California for reducing the state's carbon footprint and environmental pollution. The novelty of the technology is that IR does not heat up the medium, which is energy efficient. The walnut surface can be quickly heated to a high temperature because the wet bulb temperature of the surrounding air of walnuts is no longer the limiting factor it was in hot-air drying. At the same time, the penetration of IR provides more efficient heating and drying. The research also showed that we can afford to heat walnuts to 149°F (65°C) for drying compared to the current 109°F (43°C) hot-air drying without negatively affecting the product quality, which also makes the new process more efficient.

During the past several years, through the strong support of partners and funding agencies, such as the EISG programs of the California Energy Commission (CEC), the California Walnut Board, United States Department of Agriculture - Agricultural Research Service (USDA-ARS), California Rice Research Board, walnut equipment and processing companies, infrared equipment manufacturers, and the University of California, Davis, the team systematically investigated and proved the technical feasibility of using pre-separation of walnuts based on moisture contents and IR heating as energy efficient technologies for drying walnuts and a variety of other agricultural and food products. The drying method had been successfully tested using a mobile IR dryer on a pilot scale. It was necessary to develop and design a larger IR walnut pre-drying system for demonstrating the advantages of the new walnut drying method, further improving both energy efficiency and product quality.

Project Objectives

The main objective of this proposed project was to commercially demonstrate the novel energy-efficient drying technology and quantify both energy savings and quality improvements.

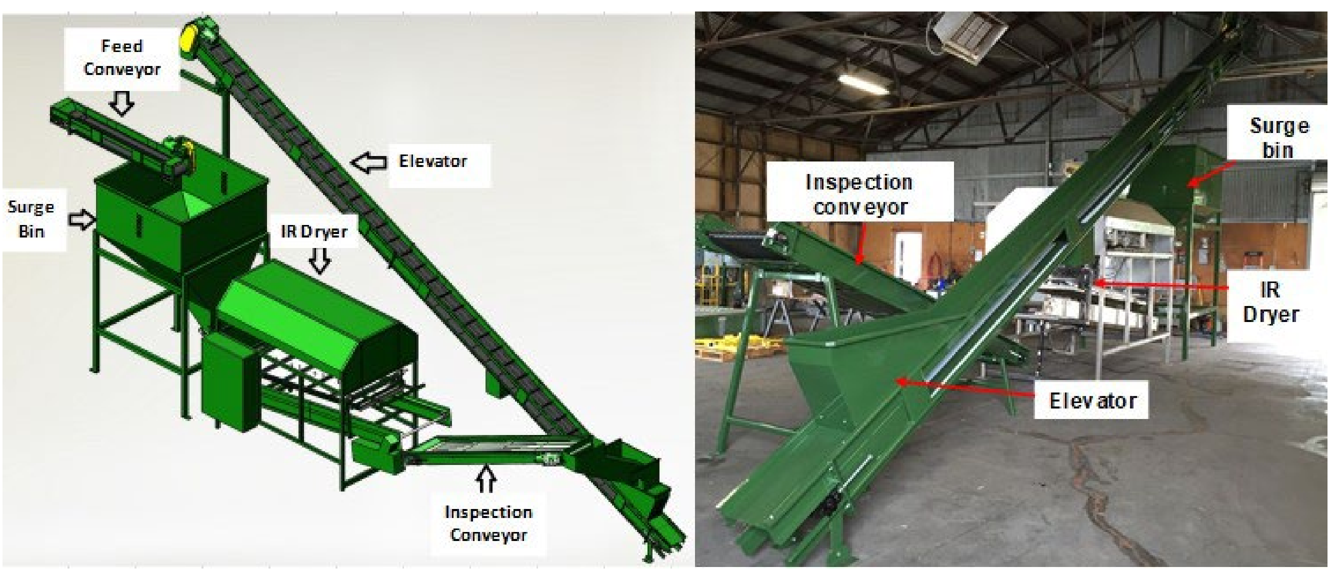
To achieve the proposed goal, the demonstration tasks were performed in two phases. In the first phase a pilot scale IR drying system with a capacity of 1-2 ton per hour was built, tested and demonstrated. The optimum operation and design parameters for the commercial system were established based on test results of the pilot system. In the second phase, a commercial-scale drying system with a capacity of 10-15 tons per hour (tph) was built, tested, and demonstrated at Emerald Farms. The team successfully:

- Designed, built, and installed a pilot-scale IR drying system that optimized the design and operation parameters and quantified product quality.
- Designed, built, and installed a commercial-scale IR drying system that optimized the operation parameters of the commercial system and quantified product quality.
- Documented the benefits in energy savings, reductions in environmental pollution, and product-quality improvements of the new IR drying technology, along with walnut pre-separation before drying on a commercial scale.
- Demonstrated the viability and feasibility of the new energy-efficient drying technology and its reduced cost.
- Disseminated the benefits of the technology to nut processors for further penetration into the marketplace.

Fabrication of Pilot-Scale Infrared Walnut Dryer

The pilot scale IR walnut dryer was designed and fabricated in collaboration with Wizard Manufacturing Inc., in Chico, California. Figure 1 and Figure 2 show the schematic drawing of the IR walnut dryer where its emitters are powered by natural gas. The dryer has a designed capacity of 1-2 tph. The dryer consists of five major parts: the feed conveyor, surge bin, IR dryer cabinet, inspection conveyor, and return conveyor. The feed conveyor carries the wet walnuts from the hulling line and delivers them to the surge bin at a controlled rate to maintain a uniform quantity of walnuts in the surge bin. The surge bin receives the product from the hulling line and acts as a bank to consistently feed the IR dryer at a predetermined rate through the feed control valves. The IR dryer cabinet contains catalytic infrared emitters and a metallic conveyor to convey the walnuts under the IR emitters. Temperature-controlled burner panels and a variable-speed conveyor belt allow testing of the drying process through a range of IR heating temperatures and exposure and heating times. The IR dryer is 3 feet wide and contained 6 infrared emitters. Four emitters are 1.5 x 3 feet (ft), and two emitters are 1 x 3 ft. The total area under the IR emitters was 24 ft^2. The emitters are separated by a 2-inch gap to allow vapor to release from the walnuts. The conveyor and the emitters are placed at an angle of 10° to the horizontal to improve the availability and circulation of air and increase the combustion efficiency of the emitters. The walnuts were conveyed under the emitters by the conveyor, placed at 6 cm below the emitters. The residence/heating time of walnuts is controlled by monitoring the walnuts' temperatures. The inspection conveyor is used for collecting samples for quality inspection and cooling the nuts. The return elevator is used to carry the dried nuts to the main hot-air drying bins. It can also be used to fill the surge bin if two passes of IR drying are required.

Figure 1: Different Components of Pilot Scale Infrared Dryer



Source: UC Davis

Figure 2: IR Drying Unit of Pilot Scale Dryer (left) and Surge Bin (right)

Source: Emerald Farms, Maxwell, CA

Drying Tests With Pilot Scale Infrared Dryer

The pilot scale IR walnut dryer was successfully designed, built, and installed at the commercial walnut drying facility of Emerald Farms in Maxwell, California. Drying tests with the pilot scale IR dryer were performed to optimize the design and operation parameters and quantify the product quality. The effects of operating parameters of the pilot scale IR walnut dryer, including heating time and product temperatures on drying characteristics and energy consumption, were all evaluated. The quality and shelf life of the walnuts dried with IR pre-dryer and hot air dryer were measured and compared with those of walnuts dried without IR pre-drying.

Experimental Methods

Walnuts: Freshly harvested walnuts of Chandler variety with different initial moisture contents (IMCs) were used to conduct the drying tests. The walnuts were sorted into two groups (high and low moisture) based on their moisture contents using an air knife. The percentages of sorted walnuts were calculated from the low and high moisture conveyer streams and found to be about 47± 2 percent and 53± 1 percent for low and high MC walnuts, respectively.

Three drying tests categorized as Test one (IR-40°C), Test two (IR-45°C), and Test three (IR-50°C) were conducted to evaluate the drying performance of the pilot scale IR drying system. The sorted walnuts with high moisture were pre-dried in the IR dryer by heating the walnuts to kernel (kernel) temperatures of 104°F (40°C), 113°F (45°C) and 122°F (50°C). The kernel and surface temperatures of walnuts were measured and monitored during the IR pre-drying (Figure 3). The IR heating times required to obtain the kernel temperatures of 104°F (40°C), 113°F (45°C) and 122°F (50°C) were 150, 180, and 240 s. The drying capacities were 0.56 tph, 0.41 tph, and 0.32 tph during Test one, two, and three, respectively (Figure 1). The IR pre-dried walnuts were conveyed to one of the drying bins (Bin A1) and dried using hot air to the target moisture of 8 percent. To compare the drying characteristics and energy use of different walnut categories, the nearby bins A2, A3 and A4 were filled with high moisture (sorted), low moisture (sorted) and mixed moisture (unsorted) walnuts, respectively, and dried using hot air to the target moisture of 8 percent.

Figure 3: IR Pre-Drying Walnuts

Hot air drying (HAD): Four bins (A1, A2, A3 and A4) in the same row that utilized hot air from a common blower and a burner for drying were selected to conduct the tests. Bin A1 was filled with the IR pre-dried walnuts, Bin A2 was filled with sorted walnuts (with high MC) without IR pre-drying, Bin A3 contained sorted walnuts (with low MC), and Bin A4 was used to dry the mixed walnuts (unsorted). During the drying process, drying air temperature was measured at three locations (bottom, center, and top) and recorded over drying time. Also, the air speed was measured at nine locations on the top surface for each bin. The experimental set-up is shown in Figure 4. The four bins were equipped with built-in moisture sensors, which provided the average moisture content of the walnuts during drying. The drying was stopped when the moisture content indicated by the sensors reached 8 percent, similar to current practices in the industry.

Sampling of walnuts to monitor drying process: To monitor the hot-air drying process in the four bins, walnut samples were collected when the moisture content of walnuts (indicated by built-in moisture sensors) reached 12 percent, 10 percent and 8 percent. To collect the walnut samples, three metal screen baskets filled with about 150 walnuts were buried in each of the drying bins at the center position (about 85 cm from the surface and 60 cm away from the bin walls), as shown in Figure 4. The metal baskets were taken out of the bins when the moisture content of walnuts reached MCs of 12, 10, and 8 percent, respectively. The walnut samples from the baskets were transferred to Ziplock bags and labeled with the date, bin number, target moisture content and time. The Ziplock bags were stored in the freezer and taken to the Biological and Agricultural Engineering Department at U.C. Davis and used for both MC determination and quality analysis.

Figure 4: Experimental Set-Up for Hot-Air Drying of IR Pre-Dried Walnuts

Source: Emerald Farms, Maxwell, CA

Moisture Content: The walnut kernels were extracted using a walnut cracker. The shells and kernels were then separately placed in pre-weighed aluminum weighing dishes and weighed using an electronic balance (Denver Instrument, Arvada Co., USA) with an accuracy of 0.01 g. The shells and kernels were dried in an air oven at 221°F (105°C) for 24 hours. Dried samples were taken from the oven, cooled, then weighed again. The MC was determined for the shells and kernels based on the initial and final (dry) sample weight, using the following equation:

$$MC_{wb} = \frac{W_i - W_d}{W_i} \times 100$$

where MC_{wb} is moisture content on wet basis, and W_i and W_d are the initial and dry sample weights, respectively. The MC of whole nuts was determined by the following:

$$MC_{wb} = \frac{(W_{si} - W_{sd}) + (W_{ki} - W_{kd})}{(W_{si} + W_{ki})} \times 100$$

W_{si} and W_{ki} are initial weights (wet) of shell and kernel and W_{sd} and W_{kd} are the final weights (dry) of shells and kernels, respectively. The moisture contents of samples were calculated and reported on a wet weight basis.

Temperature and air speed: The surface (shell) and kernel temperature of walnuts during IR heating was measured using an infrared camera (FLIR E40). Air temperature entering the fan of drying bins was measured using a thermometer (UEI, AQM4). The temperature in the dryer bins were measured at the bottom, center and top. Three thermocouples (Type T, time constant 0.15 s) were inserted at each location and connected to a data logger (OM-CP-OCTTEMP-A) as presented in Figure 3. The temperature was measured in 5 min intervals and recorded over the drying time. The air speed through the drying bins was measured using a digital anemometer (Dwyer Instruments, INC.).

Energy consumption: Energy consumed during IR drying includes natural gas consumed by IR emitters and electricity consumed in operating the vibratory feeder, chain conveyor, inspection conveyor and feeding conveyors. The gas consumption was measured using a gas flow meter (Quimeter, 97-S) during IR heating. The electricity was measured using an AC clamp meter. The energy consumption from IR drying was calculated in kJ. The energy consumption during hot air drying was calculated using the following equation:

$$Ec = \rho_a \, A \, V \, cp_a \, \Delta T \, t$$

Ec is the energy consumption (kJ), ρ_a is the air density at hot air temperature (kg/m^3), A is the bin area (m^2), V is the air velocity through the bin (m/min), cp_a is the specific heat of air (kJ/kg. °C), ΔT is the temperature difference between air inlet to the fan and air inlet to the drying bin (°C), and t is the drying time, expressed in minutes.

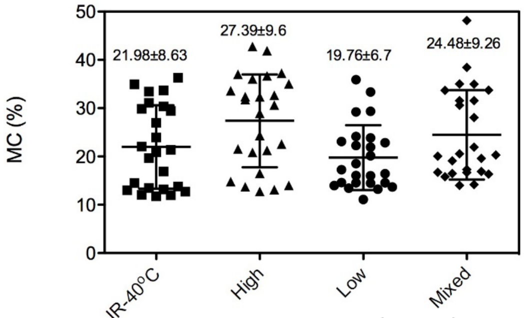
Statistical Analysis: The statistical analysis was performed using SPSS-IBM 19.0 software (SPSS, Chicago, IL, USA). One-way analysis of variance (ANOVA) was used to investigate the significance of temperature effects on moisture removal of shell and kernel of IR treated walnuts.

Results of Pilot-Scale Infrared Dryer

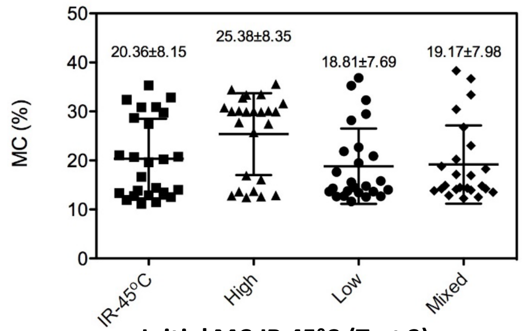
Moisture content of walnuts: The initial MC of walnuts used in the drying tests are presented in Figure 5. The unsorted (mixed) walnuts used in the three tests had initial MCs of 24.48±9.26 percent, 19.17±7.98 percent, and 21.38±10.59 percent for test one, two and three, respectively. The initial moistures of pre-sorted walnuts with low MC were 19.76±6.70 percent, 18.81±7.69 percent, and 16.80±6.80 percent and high MC were 27.39±9.6 percent, 25.38±8.35 percent, and 31.0±9.97 percent for test one, two and three, respectively. The larger standard deviation values of low and high moisture nuts showed that air knife separation is not efficient. However, sorted walnuts had a lower standard deviation compared to that of unsorted walnuts. Also, the standard deviation of low moisture sorted walnuts was less than that of high moisture sorted walnuts. This means that the sorting process minimized the variability in moisture contents of individual nuts, which is necessary to improve the drying efficiency, reduce energy consumption, and produce dried walnuts of more uniform moisture contents.

Moisture Removal During IR Heating: The moisture distributions of shell and kernel (meat) of IR-treated walnuts are presented in Figure 6. The moisture removal from shell was 6.26 percent, 5.94 percent, and 10.14 percentage points through heating the walnuts to kernel temperatures of 104°F (40°C), 113°F (45°C) and 122°F (50°C), respectively. The corresponding moisture removal from kernel was 3.61 percent, 3.64 percent, and 3.33 percent points. Moisture removal from the shell was significantly higher than that from kernel. During IR heating the shell was more quickly heated to a higher temperature than the kernel was. After IR heating, the temperatures of shell were 165°F (73.9°C), 175.8°F (79.9°C), and 193.1°F (89.5°C); for kernel, they were 104.5°F (40.3°C), 113.4°F (45.2°C), and 123.3°F (50.7°C) during test one, two, and three, respectively. Also, the corresponding moisture removals from the whole walnuts were 5.40 percent, 5.02 percent, and 7.52 percent points during Test 1, Test 2, and Test 3, respectively (Figure 7). The obtained results clearly demonstrated that by using IR heating, a significant amount of moisture could be removed from walnut shells within a very short time. At the same time, a reasonably low percentage of moisture was removed from the kernels.

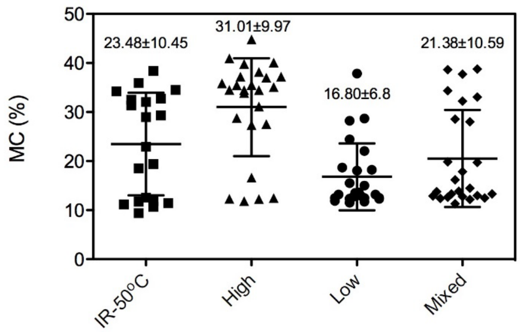
Figure 5: Initial Moisture Contents of Walnut Categories Used in Drying Tests



Initial MC-IR 40°C (Test 1)

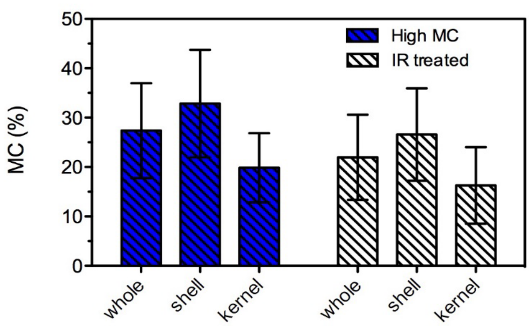


Initial MC-IR 45°C (Test 2)

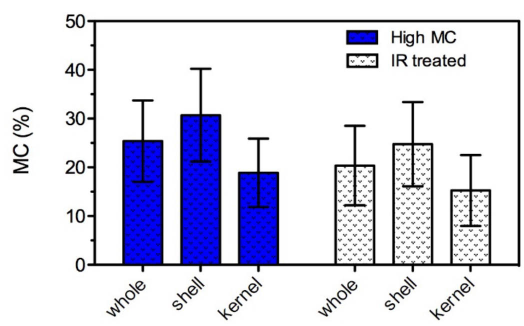


Initial MC-IR 50°C (Test 3)

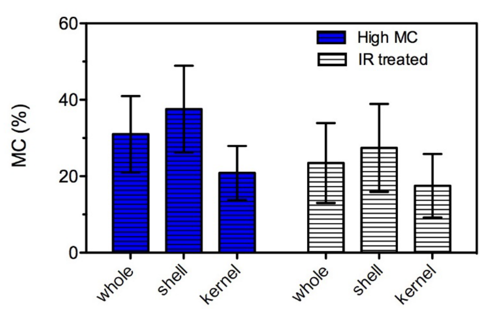
Figure 6: Moisture Contents of Whole Walnut, Shell and Kernel Before and After IR Heating



IR 40°C (Test 1)

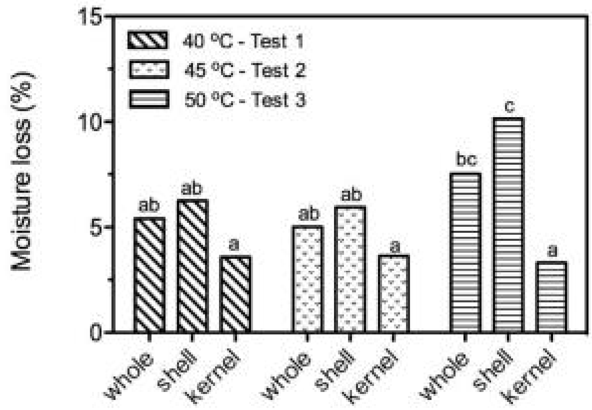


IR 45°C (Test 4)



IR 50°C (Test 3)

Figure 7: Moisture Removed From Shell, Kernel and Whole Walnut During IR Heating



Hot Air Velocity: The air speeds measured from the four bins are shown in Figure 8. The average air speed or velocity values for bins A1, A2, A3, and A4 were 1.43, 2.06, 2.32, and 2.46 m/s, respectively. These speed values revealed that that there was no uniform air flow through all the bins used for testing different walnut categories. Also, from the temperature profile of hot air in the bins, it was found that for bin A1, it took a longer time to heat the inlet air to a temperature of 105.8±1.8°F (41.0±1.0°C) compared to bins A2, A3, and A4 (Figure 9). This may be due the location of bin A1, which was located at the corner of the whole bin row. The average drying air temperatures of bins A1, A2, A3, and A4 were calculated from the temperature data collected for the entire drying period. The drying temperature of bin A1 was 98.6±1.8°F (37.0±1.0°C) and for the other three bins it was 105.8±1.8°F (41.0±1.0°C).

Figure 8: Average Air Speeds in the Drying Bins

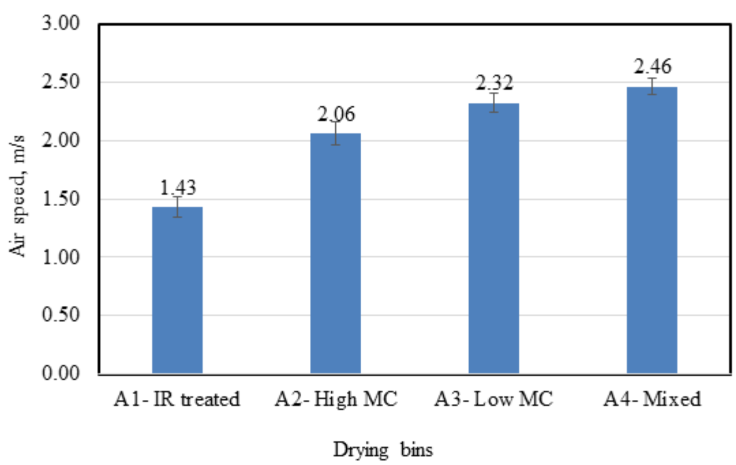
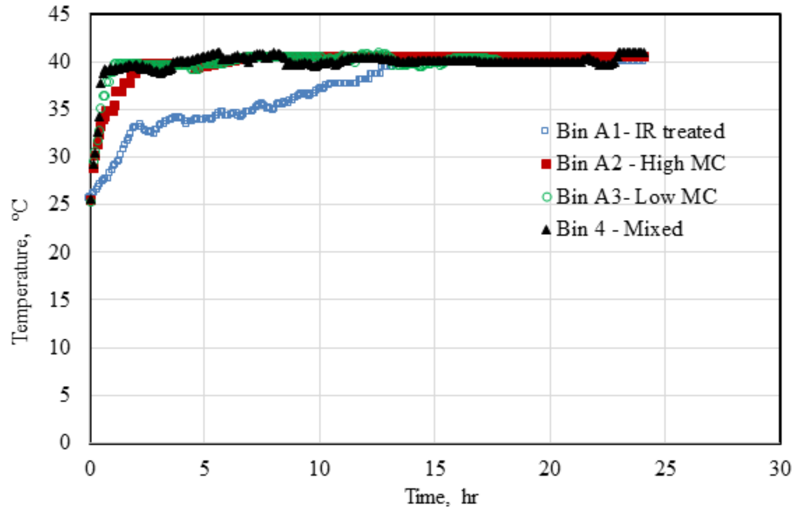


Figure 9: Temperature Profile of Hot Air During Walnut Drying at Four Bins



Moisture Content During Hot-Air Drying: The moisture contents of walnut samples collected during the hot-air drying at various target moisture contents (12 percent, 10 percent, and 8 percent) are presented in Figure 10. The measured moistures were slightly different from those read by the bin sensors. For example, when the moisture read by sensor was 12 percent, the measured moistures were 13.23 percent, 13.23 percent, 14.85 percent, and 13.58 percent for IR-treated, high-MC, low-MC and mixed walnuts during tests. The corresponding measured moistures were 8.53 percent, 8.20 percent, 7.85 percent, and 8.97 percent when the sensor reading was 8 percent (Figure 11). This means that the sensors need to be frequently calibrated. The drying times and measured moistures for the three tests are presented in Table 1, Table 2, and Table 3. They clearly show that pre-sorting significantly reduced the drying time (especially for the sorted walnuts with low MC) when compared to the drying time of unsorted walnuts (mixed), even though the low moisture walnuts were dried at a lower air speed compared to the mixed walnuts. For example, the drying time for sorted walnuts with low MC was 855, 540, 1110 min during tests one, two, and three, respectively, while the corresponding drying time for unsorted walnuts (mixed) was 1065, 795, and 1890 min. The drying time of IR-walnuts was slightly higher than that of mixed and high-MC walnuts. This is due to a difference in drying conditions. The IR-treated walnuts were dried under low air speed and temperature. The average air temperature was 98.6±1.8°F (37.0±1.0°C) for drying bin A1, and 105.8±1.8°F (41.0±1.0°C) for drying bins A2, A3 and A4. However, IR heating led to a significant reduction in energy consumption that will be discussed in detail in the next section.

Energy Consumption: Since the actual moisture contents of dried walnuts were not the same (for example, the actual moisture contents of the four bins were 8.53 percent, 8.20 percent, 7.85 percent, and 8.97 percent when the sensor reading was 8 percent), the energy consumption to dry the walnuts to 8 percent was calculated by plotting the moisture content values and energy used, as shown in Figure 12. Regression equations were used to calculate the energy consumption to dry the walnuts to 8 percent MC. As the bins were filled with walnuts to different heights during the actual test, the capacity of walnuts in drying bins A, A2, A3 and A4 varied for the three tests.

Figure 10: Moisture Distribution of Walnut Categories at Target Moisture of 12 Percent

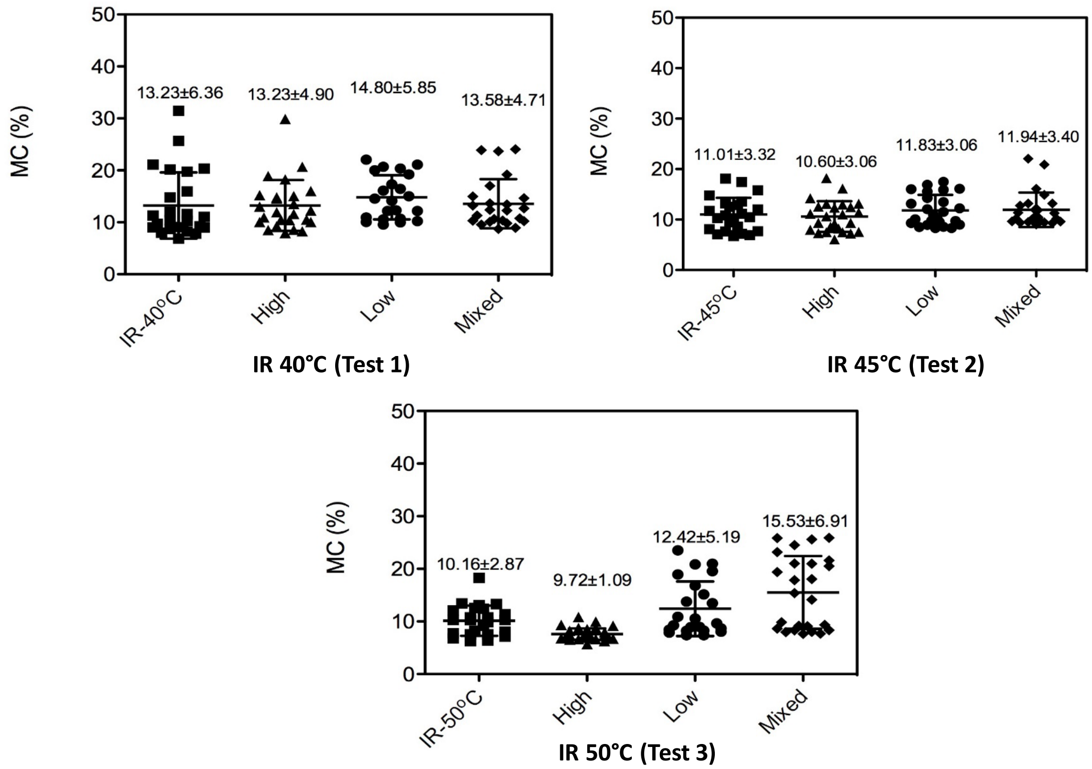
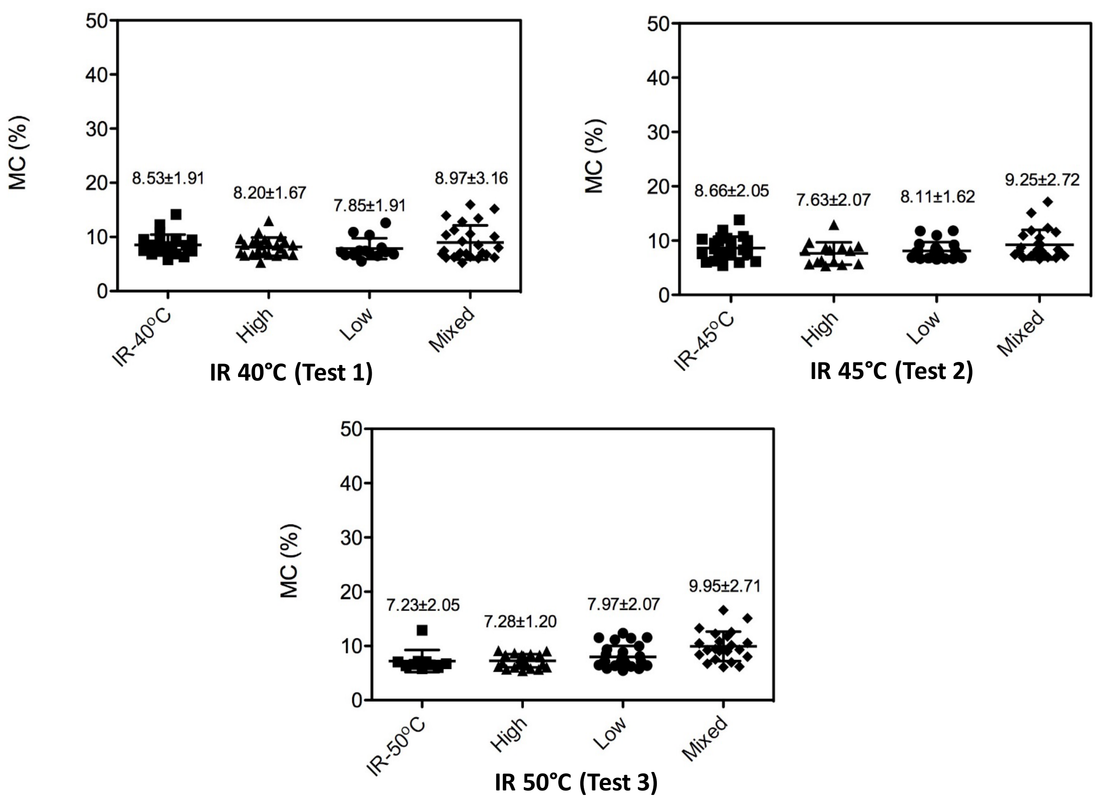


Figure 11: Moisture Distribution of Walnut Categories at Target Moisture of 8 Percent



The energy consumed by the four categories of walnuts; the sorted and IR pre-dried high moisture walnuts, sorted high moisture walnuts (without IR pre-drying), sorted low moisture walnuts and unsorted mixed walnuts for the three tests are presented in tables 1, 2, and 3, respectively. It can be seen that the energy used for drying to 8 percent MC for IR treated walnuts was less than that of high moisture walnuts (without IR pre-drying) and also mixed walnuts. This indicated that IR heating reduced the energy consumption for the whole drying process. For example, the total energy consumption during test one was 10004712, 12851455, 10375870 and 13389838 kJ per 3-ton batch for IR-treated, high MC, low MC and mixed walnuts, respectively. The corresponding total energy consumption was 8669465, 10130698, 7848309 and 12442192 kJ for test two and 14079085, 21970478, 11778389, and 23366394 kJ per batch of 3 tons (Tables 1, 2 and 3).

The energy saved by sorting walnuts using air knife and the energy saved by sorting and IR pre-drying were calculated using the equation given below.

Energy saving by sorting (%) $= \frac{EMixed - (EHM \times 0.53 + ELM \times 0.47)}{EMixed} \text{ x } 100$

Where:

EMixed - Energy consumed by the unsorted mixed walnuts in kJ/ton

EHM - Energy consumed by the sorted high-moisture nuts in kJ/ton

ELM - Energy consumed by the sorted low-moisture nuts in kJ/ton

EIR - Energy consumed by the sorted and IR pre-dried nuts in KJ/ton

The energies saved from sorting were 18.77 percent, 28.80 percent and 23.01 percent for Test 1, Test 2 and Test 3, respectively. The energy savings from IR pre-drying alone were calculated by the difference in energy consumption between the high moisture nuts without IR pre-drying and with IR pre-drying treatment (EHM and EIR) and the values were found as 11.68 percent, 12.81 percent and 11.70 percent for Test 1, Test 2, and Test 3, respectively.

Figure 12: Relationship Between Moisture Content and Energy Consumption for Test 1 (IR 104°F [40°C])

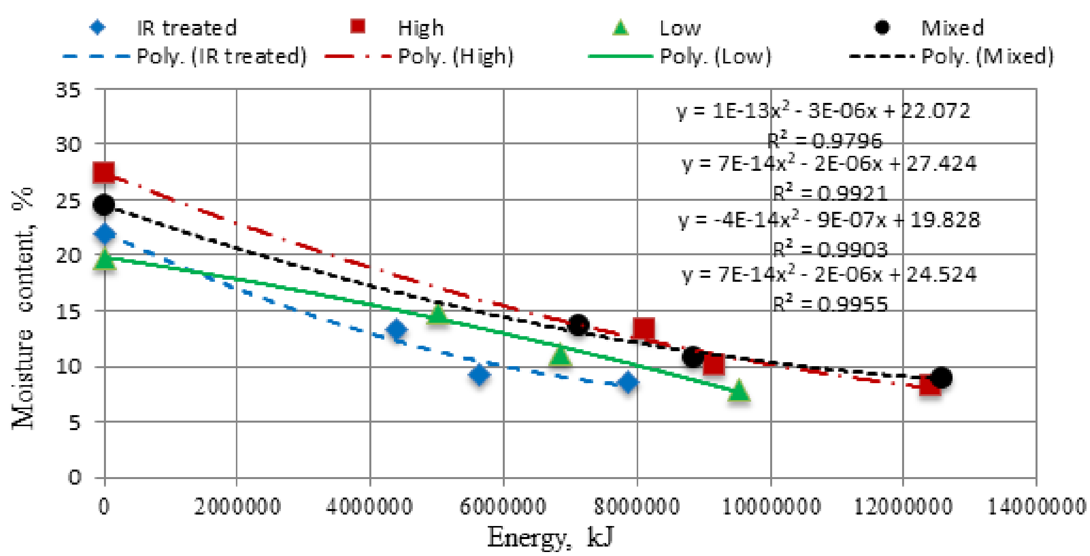


Table 1: Energy Consumption and Savings by Sorting and IR Pre-Drying of Walnuts to Kernel Temperature of 104°F (40°C)

Description	IR pre-dried to 40°C kernel temperature	Sorted high moisture walnuts	Sorted low moisture walnuts	Unsorted (mixed) walnuts
Initial MC of walnuts, %	27.39	27.39	19.76	24.48
Moisture removed by IR pre-drying, %	5.41	NA	NA	NA
MC at start of HAD, %	21.98	27.39	19.76	24.48
MC after HAD, %	8.53	8.2	7.85	8.97
Drying time, min	1470	1255	855	1065
Air velocity, m/s	1.43	2.06	2.32	2.46
Average hot air temperature, °C	37	41	41	41
Energy used in IR drying kJ/batch (3 ton)	1,501,541	NA	NA	NA
Total energy used in drying to 8% MC, kJ/batch (3 ton)	10,004,712	1,285,1455	10,375,870	13,389,838
Energy used to dry 1 ton of wet walnuts to 8% MC, kJ/ton	3,735,082	4,283,686	3,458,361	4,796,242
Energy saving due to sorting process (%)		18.77		
Energy saving due to IR pre-drying (%)		11.68		

Table 2: Energy Consumption and Savings by Sorting and IR Pre-Drying of Walnuts to Kernel Temperature of 113°F (45°C)

Description	IR pre-dried to 45°C kernel temperature	Sorted high moisture walnuts	Sorted low moisture walnuts	Unsorted (mixed) walnuts
Initial MC of walnuts, %	25.38	25.38	18.81	19.17
Moisture removed by IR pre-drying, %	5.02	NA	NA	NA
MC at start of HAD, %	20.36	25.38	18.81	19.17
MC after HAD, %	8.66	7.63	8.11	9.25
Drying time, min	984	990	540	795
Air velocity, m/s	1.43	2.06	2.32	2.46
Average hot air temperature, °C	37	41	41	41
Energy used in IR drying kJ/batch (3 ton)	1,835,399	NA	NA	NA

Description	IR pre-dried to 45°C kernel temperature	Sorted high moisture walnuts	Sorted low moisture walnuts	Unsorted (mixed) walnuts
Total energy used in drying to 8% MC, kJ/batch (3 ton)	10,158,416	10,130,698	7,848,309	12,442,192
Energy used to dry 1 ton of wet walnuts to 8% MC (kJ/ton)	3,386,139	3,834,003	2,584,427	4,560,038
Energy saving due to sorting process (%)		28.80		
Energy saving due to sorting and IR pre-drying (%)		12.81		

Table 3: Energy Consumption and Savings by Sorting and IR Pre-Drying of Walnuts to Kernel Temperature of 122°F (50°C)

Description	IR pre-dried to 50 °C kernel temperature	Sorted high moisture walnuts	Sorted low moisture walnuts	Unsorted (mixed) walnuts
Initial MC of walnuts, %	31.01	31.01	16.80	21.38
Moisture removed by IR pre-drying, %	7.53	NA	NA	NA
MC at start of HAD, %	23.48	31.01	16.80	21.38
MC after HAD, %	7.23	7.28	7.97	9.95
Drying time, min	2131	2181	1110	1890
Air velocity, m/s	1.43	2.06	2.32	2.46
Average hot air temperature, °C	37	41	41	41
Energy used in IR drying kJ/batch (3 ton)	2168640	NA	NA	NA
Energy used in HAD, kJ/batch (3 ton)	11059523	21970478	11778389	20744913
Total energy used in drying to 8% MC, KJ/batch (3 ton)	13228163	15971235	11778389	20744913
Energy used to dry 1 ton of wet walnuts to 8% MC	4381630	5323745	3926080	6914971
Energy saving due to sorting process (%)		23.01		
Energy saving due to sorting and IR pre-drying (%)		17.70		

Table 4: Energy Savings by Sorting and IR Pre-Drying of Walnuts to Kernel Temperatures of 104°F (40°C), 113°F (45°C), and 122°F (50°C)

Description	IR pre-drying to 40°C	IR pre-drying to 45°C	IR pre-drying to 50°C
Initial Moisture content (%)	27.39	25.38	31.01
IR pre-drying time (s)	150	180	240
Moisture content after IR drying (%)	21.98	20.36	23.48
Moisture removal during IR drying (% points)	5.41	5.02	7.53
Energy saving by sorting using air knife	18.77	28.80	23.01
Energy saving by IR pre-drying, %	11.68	12.81	17.70
Total Energy saving by sorting and IR pre-drying compared to drying of unsorted walnuts, %	29.45	34.01	40.71

Quality and Shelf Life of Walnuts

The effect of IR pre-drying on the quality of walnuts, including the color (lightness) of walnut kernels, peroxide value (PV) and free fatty acid (FFA) content of the walnut oil extracted from the walnut kernels, were determined. The nut surface color was measured using the Minolta colorimeter (CR-200, Osaka, Japan) and the Commission Internationale de L'Esclairage (CIE) L (lightness) value was determined. Figure 13 shows the cracked walnut kernels used for measuring the L values.

Figure 13: Dried Kernels

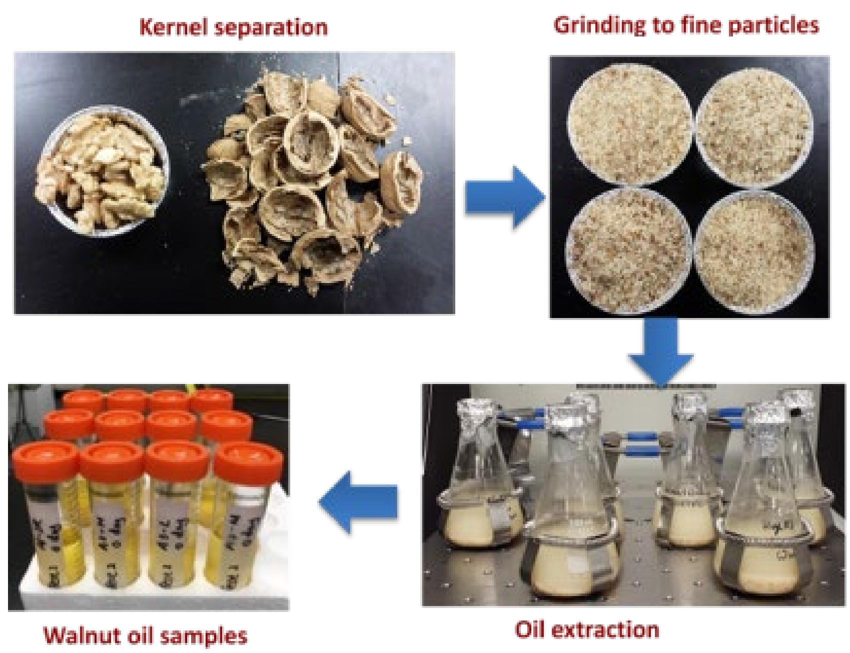
a b c d

(a) combined IR (122°F [50°C]) and hot-air (HA) dried high moisture nuts (B) HA dried high moisture nuts, (c) HA dried low moisture nuts (d) HA dried mixed moisture nuts

To determine the PV and FFA values, walnut oil extraction was performed using hexane as solvent according to the procedure shown in Figure 14. Five walnut samples were cracked, and the kernel was ground into powder with a kitchen blender (Ninja, EuroPro Operating LLC, Newton, Mass.). Walnut powder and a 10-time volume of hexane was added into a 500 mL beaker, and the mixtures were stirred with a stirrer bar at room temperature and in the dark for an hour. The mixtures were then centrifuged at 5000 g at 39°F (4°C) for 5 min to remove any walnut solids. Hexane was removed from the oil and hexane mixtures using a rotary evaporator (Rotavapor model 461, Büchi, Switzerland) at 86°F (30°C). The oil was weighed and stored in 15 mL centrifuge tubes at –4°F (–20°C) until further analyses. Peroxide value and FFA content of the walnut oil were determined according to the official methods Cd8-53 and Ca 5a-40, respectively, of the American Oil Chemists Society (AOCS, 1998).

To investigate the effect of IR pre-drying on the storage stability of walnuts over the storage period of two years, an accelerated shelf life study was conducted by storing walnuts for a storage period of 20 days at 95°F (35°C) and 43.1 percent relative humidity. During storage, the walnuts were kept in a paper bag to prevent moisture build-up and mold growth. The storage conditions simulated an approximately 2-year storage period at 39°F (4°C) according to a Q10 value of 3.4 at 95°F (35°C) (Wang et al., 2006). The Q10 value is a ratio that relates the reduction of shelf life with storage temperature when the temperature increases by 50°F (10°C). Walnut samples were collected after 0, 5, 10, and 20 days of incubation, which corresponded to 0, 6, 12, and 24 months of storage at 39°F (4°C). Quality attributes including nut surface color, moisture loss, and peroxide value of oil extracted from the nut were analyzed.

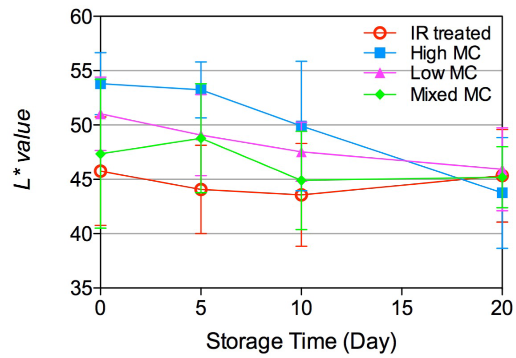
Figure 14: Walnut Oil Extraction Process Flow Chart for Oil Quality Analysis



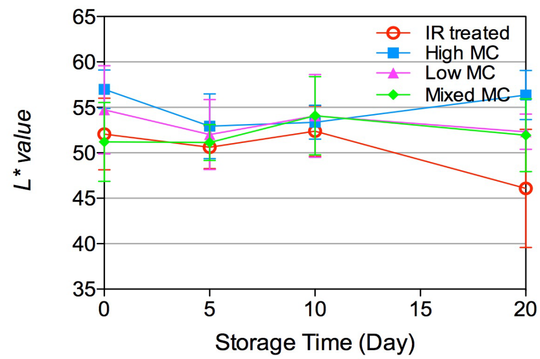
The color lightness values (L*) of all the three tests showed that all the hot-air dried nuts, including the IR pre-dried walnuts (Figure 15), had a higher L* value than the industrial requirement (L* value of 40), even after the storage period of 20 days. The color lightness value of IR pre-dried walnuts on 0-day storage was slightly lower than that of the hot-air dried high-moisture walnuts, but the difference was not significant, indicating that IR pre-drying had no significant effect on the color of the walnuts. The color values did not change significantly during the storage periods for all three IR pre-drying treatments.

The PV values of all the four walnut samples including the IR pre-dried walnuts were less than 0.5 Meq/kg of oil, for all three drying tests, Test one (IR-40°C), Test two (IR-45°C) and Test three (IR-50°C), as shown in Figure 16. There was no definite trend in the change of PV value during the 12 months of storage. However, after 24 months of storage, the PV values significantly increased for all four dried-walnut samples of all three tests. Walnuts with a PV value of less than 1 Meq/kg of oil are considered safe for sale by the walnut industry, which means that the IR pre-dried walnuts could be stored for at least one year without affecting the quality, as indicated by the color and PV values. No significant difference in the color lightness value (L*) and PV values of IR pre-dried walnuts and hot-air dried walnuts were observed during the storage period of 20 days.

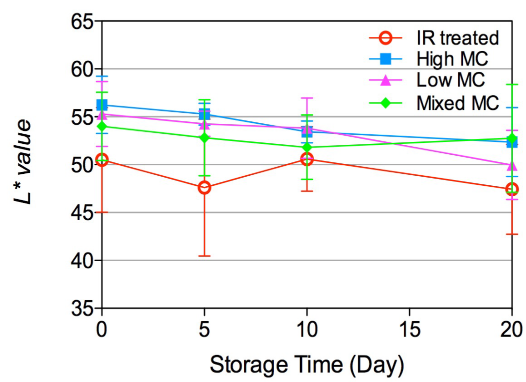
Figure 15: Effect of Storage on Lightness of Walnuts Dried With IR Pre-Drying and HA and Walnuts Dried by HA



a. IR 40°C (Test 1)

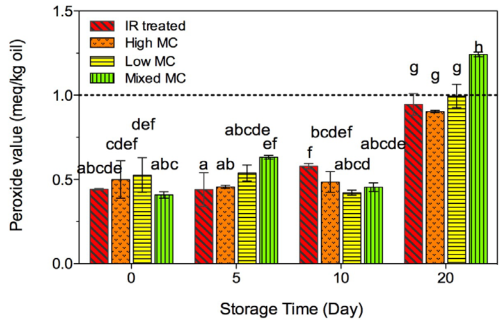


b. IR 45°C (Test 2)

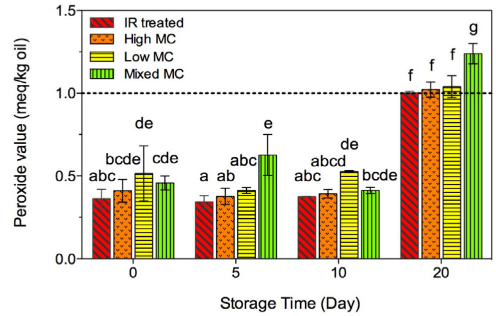


C. IR 50°C (Test 3)

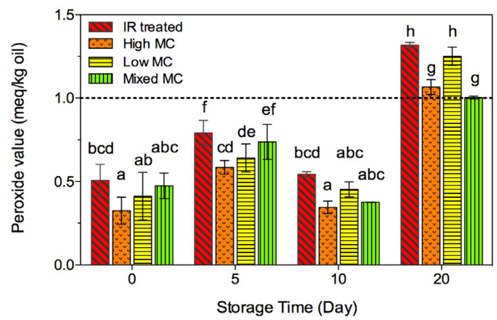
Figure 16: Effect of Storage Time on Peroxide Values of Walnuts Dried with IR Pre-Drying and HA and Walnuts Dried by HA



a. IR 40°C (Test 1)

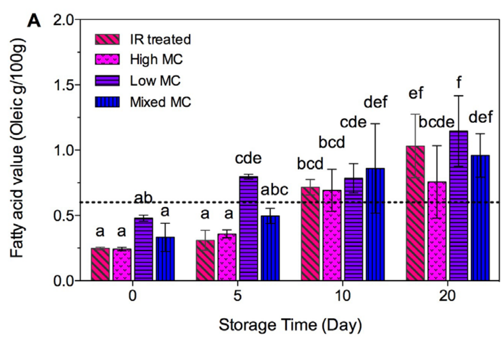


b. IR 45°C (Test 2)

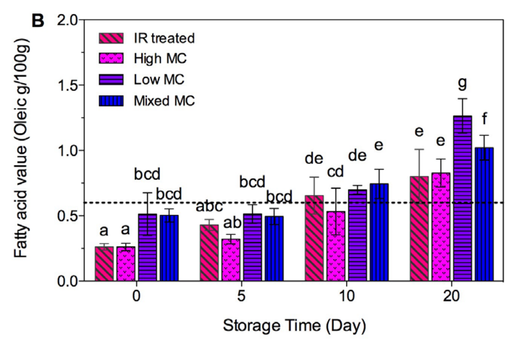


c. IR 50°C (Test 3)

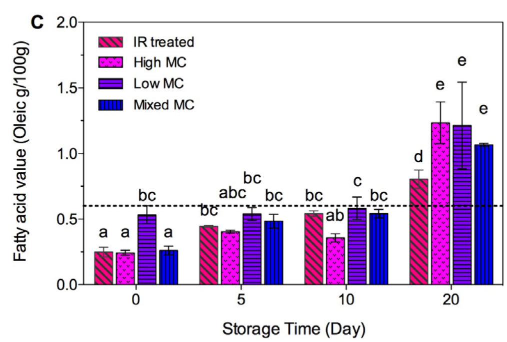
Figure 17: Effect of Storage Time on Free Fatty Acid Values of Walnuts Dried With IR Pre-Drying and HA and Walnuts Dried by HA



a. IR 40°C (Test 1)



b. IR 45°C (Test 2)



c. IR 50°C (Test2)

The FFA values for the four walnut samples of the three tests are shown in Figure 17. The FFA value of oils extracted from IR pre-dried walnuts at 104, 113, and 122°F (40, 45 and 50°C) were 0.247, 0.262, and 0.249 g/100g, respectively, without any significant difference. The oil extracted from low initial MC walnuts were as high as 0.50 g/100 g, which might be caused by over drying of low MC walnuts to below 5 percent MC. The FFA value increased with increases in storage time. An FFA value less than 0.6 g/100g indicates acceptable walnut quality recommended by the walnut industry in California (Wang et al., 2007). The results indicated that IR pretreatment has no negative affect on the FFA value of walnut oil.

The studies on quality and shelf life of IR pre-dried walnuts showed that there was no significant difference in the color lightness value (L*), PV, and FFA values of IR pre-dried walnuts and the hot-air dried walnuts observed during the storage period of 20 days. The IR pre-dried walnuts can be stored for less than 1 year while maintaining the color, PV, and FFA values stipulated by California's walnut industry.

Conclusions

A pilot scale infrared walnut dryer with a targeted capacity of 1-ton per hour was designed and built in collaboration with Wizard Manufacturing Inc., in Chico, California. The dryer was tested at Emerald Farms in Maxwell, California. The hulled and washed walnuts were sorted into two moisture groups of low- and high-moisture, and walnuts with high-moisture content were IR pre-dried to three different kernel temperatures of 104, 113, and 122°F (40, 45, and 50°C) using the pilot scale IR dryer. The IR pre-dried walnuts were conveyed to the hot-air drying bins and were dried to a moisture content of 8 percent. The results showed that IR heating for 150, 180, and 240 s resulted in the walnut kernel temperatures of 104, 113, and 122°F (40, 45, and 50°C), respectively. IR heating resulted in significant moisture removal from the walnut shell compared to the kernel. The energy consumption studies showed that sorting the walnuts into two moisture groups and drying them separately could save up to 28.80 percent compared to drying the unsorted walnuts by preventing over drying. The energy savings by IR pre-drying alone were found to be 11.68 percent, 12.81 percent, and 11.70 percent for IR heating the walnuts to kernel temperatures of 104, 113, and 122°F (40, 45, and 50°C), respectively. The quality and shelf-life studies of IR pre-dried walnuts showed that there was no significant difference in the color lightness (L*), PV, and FFA values of IR pre-dried walnuts compared to those of the hot-air dried walnuts during the storage period of two years. The IR pre-dried walnuts can be stored for about one year while maintaining the color, PV, and FFA standards set by the industry. The IR drying experiments with the pilot scale IR dryer showed that IR heating for 240 s to a kernel temperature of 122°F (50°C) resulted in the highest moisture removal compared to the other two IR pre-drying treatments, without affecting the quality and shelf life of dried walnuts. Based on the results, it was decided to design and build the commercial scale IR dryer to heat the walnuts to a kernel temperature of about 122°F (50°C).

CHAPTER 2: Commercial-Scale Infrared Walnut Pre-Drying System

Fabrication of Commercial-Scale Infrared Walnut Dryer

The objectives for the second phase of this project were to design, build, and test a commercial scale IR dryer walnut dryer with a targeted capacity of 10 tph. The commercial scale IR walnut dryer was designed and fabricated in collaboration with Wizard Manufacturing Inc., in Chico, California. From the design of the pilot scale dryer, the team found that an IR emitter heating area of 24 ft^2 resulted in a capacity of 0.32 tph for IR heating of walnuts for 240 s to a kernel temperature of 122°F (50°C). To design a dryer with a capacity of 10 tph, 750 ft^2 of emitter area is therefore required. It was decided to have 64 emitters of 2 ft x 6 ft, with a total emitter area of 768 ft^2. The 64 emitters require a 128 ft length and a 6 ft width. The Emerald Farms drying facility was measured and a suitable place was chosen for the installation of the commercial-scale dryer. Because 15 percent slope to the horizontal is required for air flow to improve the combustion efficiency, the total height required for the 64 emitters was about 33 feet. Since it would be both difficult and unfeasible to build 64 emitters in one section, the dryer was separated into 4 sections containing 16 emitters each, as shown in Figure 18 and Figure 19. An air gap of about 4 inches between each emitter is provided to increase air circulation to improve the combustion efficiency of natural gas. The layout for the installation of the commercial scale dryer at the Emerald Farms facility is shown in Figure 20.

Figure 18: Conveyor Assembly of Commercial Scale IR Dryer With 16 IR Emitters of 2′ x 6′

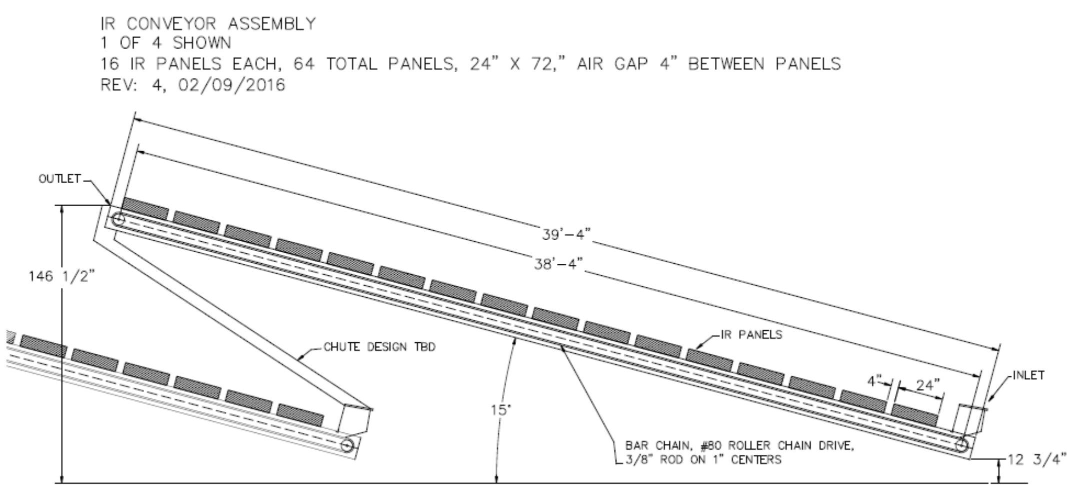


Figure 19: Conveyor Assembly Showing Four Sections With 64 IR Emitters of 2′ x 6′

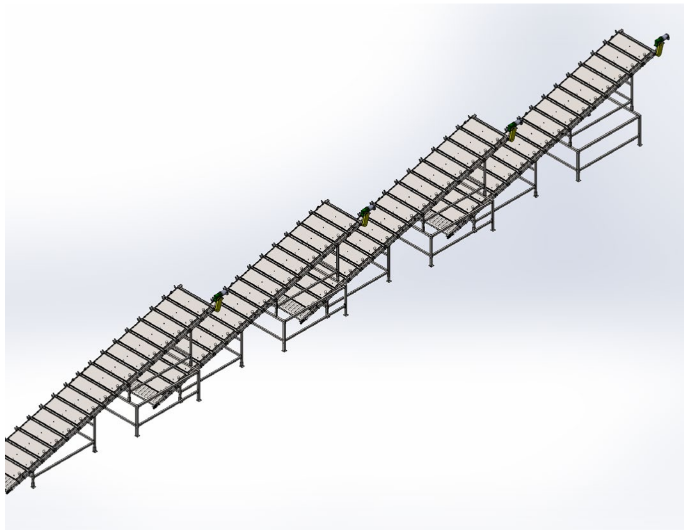
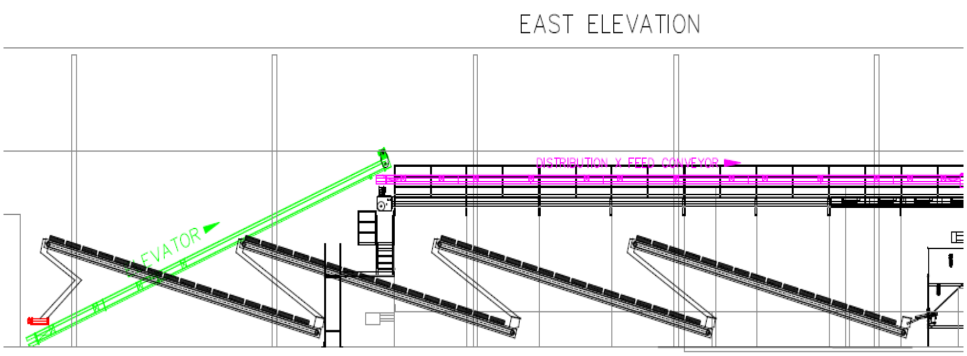


Figure 20: Design Layout of Commercial Scale Walnut Dryer



A steel mount robust enough to support the IR emitters and prevent the bottom of IR emitters from sagging and touching the walnuts is shown in Figure 21. A stainless-steel conveyor (Figure 21a) was placed about 6 cm from the emitters to convey the walnuts just below the IR emitters and improve heat transfer to the walnuts. A roller brush was provided between the emitters to rotate the walnuts when they were heated under the IR panels to improve the uniformity of heating. To facilitate the smooth transfer of walnuts from the top end of one section to another section, a sloped metallic frame was provided, shown in Figure 22. The surge bin received the walnuts from the hulling line and acted as a bank to consistently feed the IR dryer at a predetermined rate through the feed control valves. A vibratory feeder was used to distribute the walnuts over the entire conveyor width of 6 ft. The magnitude of vibration of the feeder controlled the feed rate. The conveyors of the individual IR heating sections can be operated at variable speeds to achieve the required IR heating time of 2.5 to 5 minutes. The 64 IR emitters were connected to both natural gas supply lines and electric power lines.

Figure 21: Stainless Steel Walnut Conveyor (a) and IR Emitter With Steel Mount (b)

a b

Figure 22: Conveyor System With Frame to Transfer Walnuts to the Next Stage

An inspection tower was provided at the end of the fourth IR pre-drying section for collecting samples for quality inspection (Figure 23). A return conveyor was built to carry the IR pre-dried nuts back to the hot-air drying bins.

The IR walnut dryer was installed on the western side of the drying facility of Emerald Farms, using the layout plan shown in Figure 20. The natural gas connection to the 64 IR emitters, and the electrical connection to the preheaters in all 64 emitters were provided. The control panel to control and monitor the electrical connection and vary the speed of the four conveyor chains was also provided.

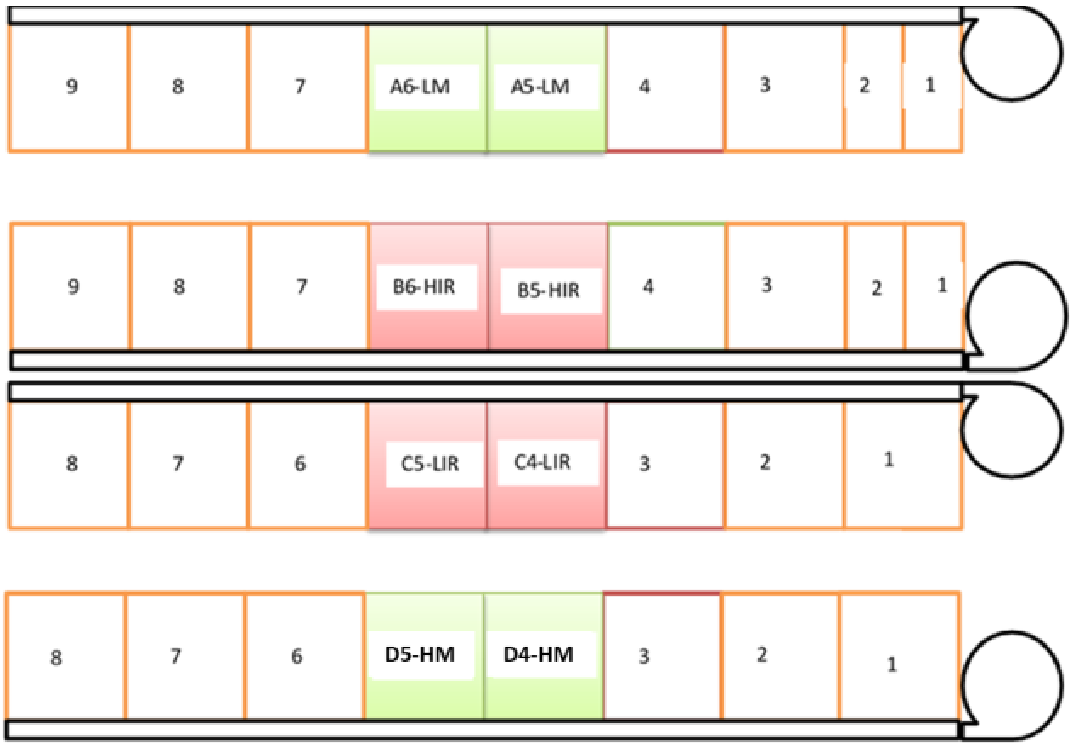
Figure 23: IR Dryer Installed With Surge Bin (left) and Inspection Tower (right)

Drying Tests With Commercial-Scale Infrared Dryer

The drying tests were performed to optimize the operation parameters and quantify energy savings and product quality. Preliminary trials were conducted to optimize the vibratory feeder that evenly distributes the walnuts over the conveyors. During the pre-test to burn the IR emitters, it was noticed that the power availability in the drying facility was insufficient to simultaneously preheat all the emitters. Therefore, two sections were preheated first, then the other two IR heating sections were preheated. The natural gas pressure required to maintain a uniform temperature at all IR emitters was determined before actual testing was conducted. The operating speed of the four conveyors for the IR heating sections was tested to obtain a required heating time of about 4 min to achieve a kernel temperature of 122°F (50°C).

After the operating parameters for the IR pre-drying part had been identified and established, the hot-air bins used for the drying tests were identified. Two bins in the middle of the four rows (A, B, C and D) were selected for conducting the drying tests. The two bins in the first row were filled with low-moisture nuts without IR pre-drying, and the two bins in the second and third rows were filled with high-moisture IR pre-dried walnuts and low-moisture IR pre-dried walnuts, respectively. The two bins in the fourth row were filled with high-moisture nuts without IR pre-drying, as shown in Figure 24. The second and third rows were chosen to dry the IR pre-dried walnuts and these two rows were connected by the return conveyor to carry walnuts after IR pre-drying. The plenum of the selected bins was provided with a pressure transducer to measure the static pressure of hot air and a thermocouple to measure the hot-air temperature. The static pressure and hot-air temperature were continuously recorded during the drying. The ambient air temperature and relative humidity of the air entering the blower and the surface temperature of walnuts in the bin during drying were also recorded.

Figure 24: Layout of Hot-Air Bins Selected for Conducting Drying Tests



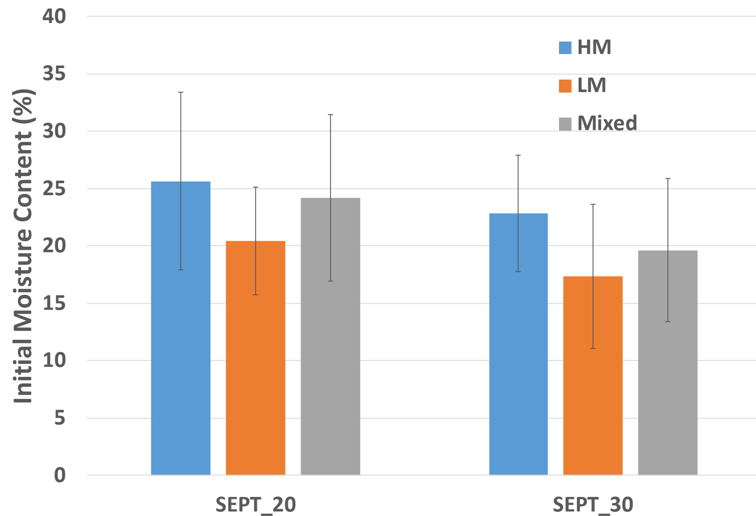
Similar to the pilot scale drying tests, to monitor the hot-air drying process in the 8 bins, walnut samples were collected when their moisture content reached 12 percent, 10 percent and 8 percent. To collect the walnut samples, three metal screen baskets filled with about 150 walnuts were buried in each of the drying bins at the center position (about 85 cm from the surface and 60 cm away from the bin walls). The metal baskets were taken out from the bins when the moisture content reached MCs of 12, 10 and 8 percent, respectively. The walnut samples from the baskets were transferred to ziplock bags and labeled with the date, bin number, target moisture content, and time. The ziplock bags were stored in the freezer and taken to the Biological and Agricultural Engineering Department at University of California (UC) Davis for MC determination and quality analysis. The moisture content, energy consumption during drying, quality and shelf life studies were performed following the procedure used for testing the pilot scale IR dryer.

Results of Commercial-Scale Dryer

Moisture Content of Walnuts

The initial moisture content of walnuts used in the drying tests on September 20, 2016 and September 30, 2016 are presented in Figure 25. The initial MCs of high, low and unsorted mixed moisture walnuts were 25.67±7.72 percent, 20.44±4.69 percent, and 24.18±7.25 percent, respectively, for September 20, 2016, and 22.88±5.08, 17.34±6.27 percent, and 19.65±6.23 percent, respectively, for September 20, 2016. The larger standard deviation values of low- and high-moisture nuts showed that the air knife separation is inefficient. The standard deviation of low-moisture sorted walnuts was less than that of high-moisture sorted walnuts.

Figure 25: Initial Moisture Content of Howard Variety Walnuts Used in the Drying Tests



Moisture Removal During Infrared Heating

In the first test on September 20, 2016, IR heating was performed with all the IR emitters working. The speed of the conveyors was adjusted to have an IR heating time of 210 seconds (Figure 26). The shell and kernel temperatures were measured at the end of the IR heating period and were found to be 163.76±14.6°F (73.2±8.1°C) and 126.32±9.9°F (52.4±5.5°C), respectively, for the high-moisture walnuts and 167±16.4°F (75.0±9.1°C) and 128.3±11°F (53.5±6.1°C), respectively, for the low moisture walnuts (Table 5).

Table 5: IR Heating Conditions and Moisture Removal During IR Pre-Drying Test 1 and Test 2

Parameters	Test 1 (9/20/2016)		Test 2 (9/30/2016)	
	HM	LM	HM	LM
Initial moisture content (%)	25.67	20.44	22.83	17.34
IR heating time (s)	210	210	225	188
Emitters used	64	64	53	45
Surface temperature, °C	73.2±8.1	75±9.1	72.6±9.5	72.5±6.7
Kernel temperature, °C	52.4±5.5	53.5±6.1	49.3±4.9	48.0±4.3
Moisture lost by IR heating, (%)	3.10±0.71	5.19±0.41	3.96±0.53%	3.62±0.65
IR walnut dryer capacity, tph	10.67	12.00	12.60	14.22

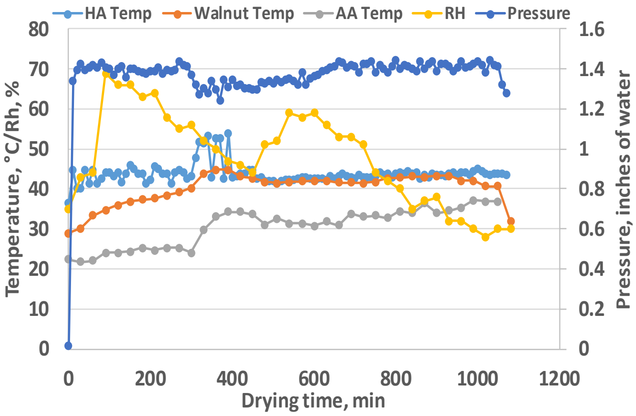
The IR heating resulted in moisture removal of 3.10±0.71 percent and 5.19±0.41 percent from the high- and low-moisture walnuts, respectively. The capacity of the IR dryer was 10.67 and 12.00 tph for high- and low-moisture nuts, respectively. For the second test, the shell and kernel temperatures were found to be 162.68±17.1°F (72.6±9.5°C), and 120.74±8.8°F (49.3±4.9°C), respectively, for high-moisture nuts and 162.5±12.1°F (72.5±6.7°C) and 118.4±7.7°F (48.0±4.3°C), respectively, for low-moisture nuts. The percentages of moisture removed during the IR pre-drying were 3.96±0.53 percent and 3.62±0.65 percent for high- and low-moisture nuts, respectively, and the corresponding IR dryer capacities were 12.60 and 14.22 tph.

Figure 26: Feed Rate Adjustment and Temperature Measurement of Walnuts for IR Pre-Dryer

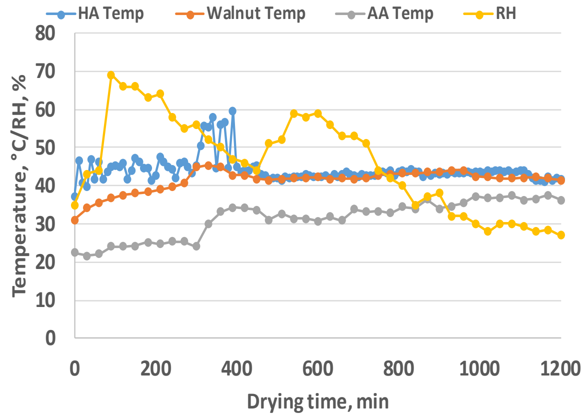
Results for Test 1

The ambient air temperature, relative humidity, hot-air temperature, static pressure of hot air at the plenum and the walnut surface temperature during hot-air drying for the eight bins used in the study for September 20, 2016 are shown in Figure 27 and Figure 28.

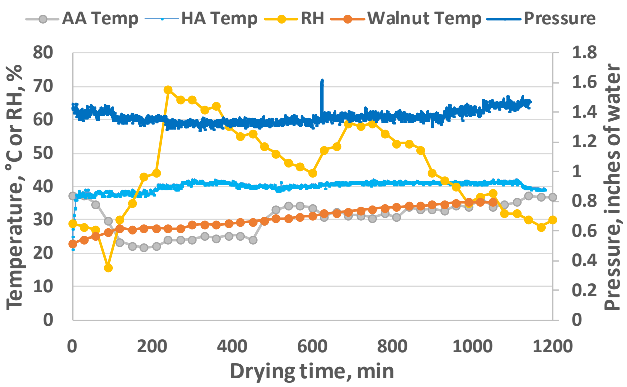
Figure 27: Hot-Air Parameters for High Moisture Nuts With and Without IR Pre-Drying (Test 1)



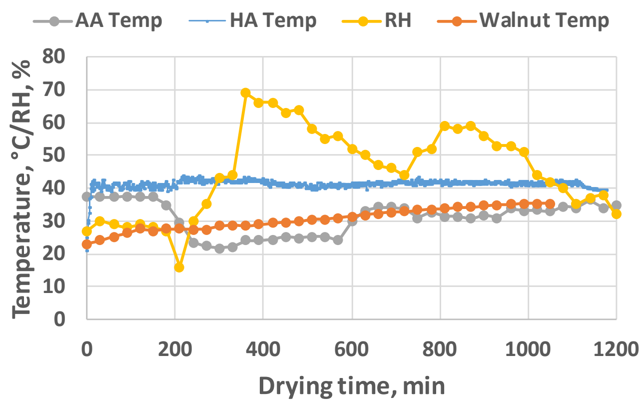
a. IR High moisture (Bin B5)



b. IR High moisture (Bin B6)

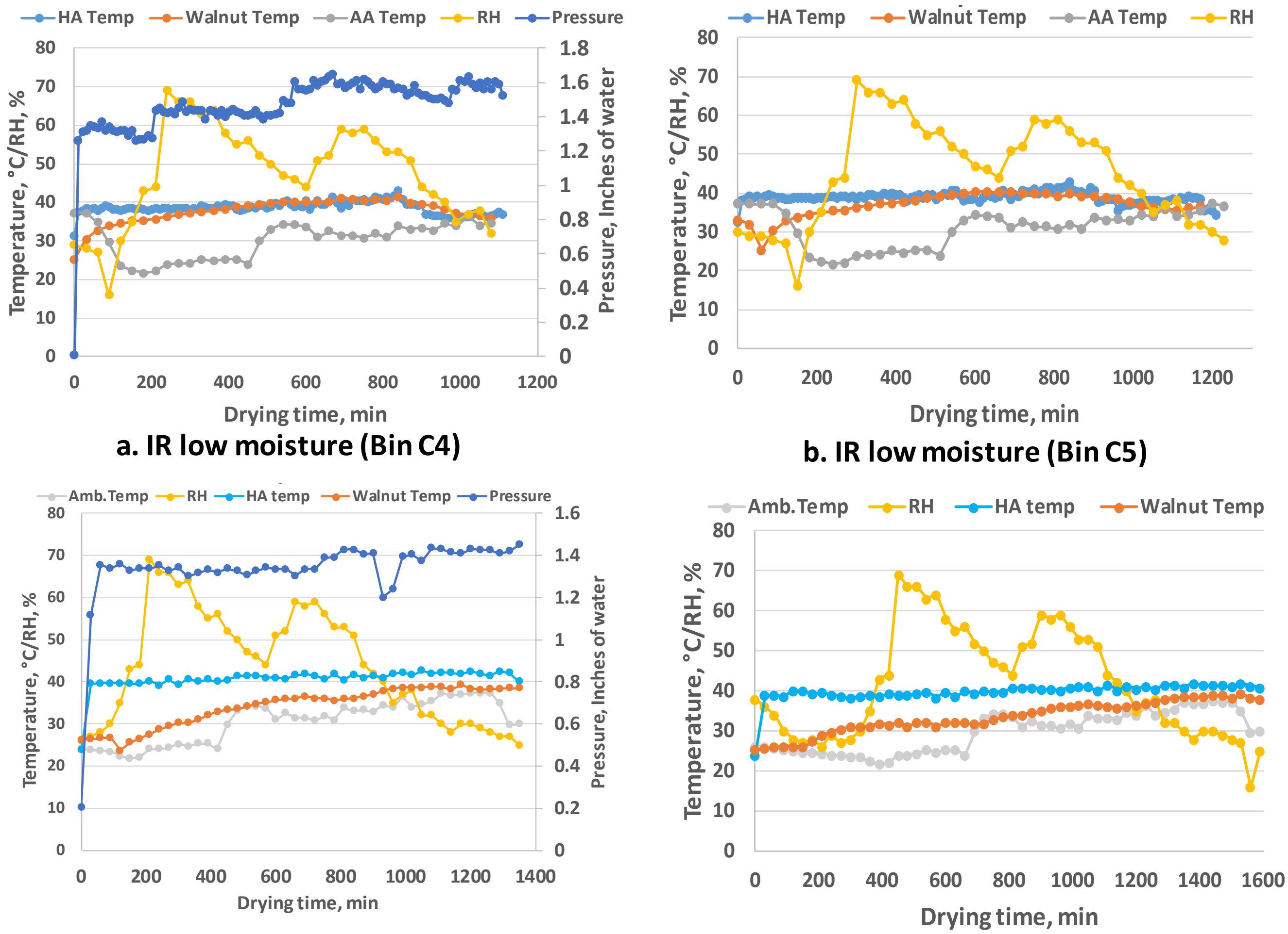


c. High moisture (Bin D4)



d. High moisture (Bin D5)

Figure 28: Hot-Air Parameters for Low-Moisture Nuts With and Without IR Pre-Drying (Test 1)



a. IR low moisture (Bin C4)

b. IR low moisture (Bin C5)

c. Low moisture (Bin A5)

d. Low moisture (Bin A6)

The average drying time, temperature of hot air and the air-flow rate for the eight hot-air drying bins calculated from the recorded parameters are provided in Figure 26 and Figure 27. The table shows that the hot-air drying time of IR pre-dried walnuts is shorter than that of walnuts without IR pre-drying for both high- and low-moisture walnuts. The low-moisture walnuts took a longer time to reach 8 percent MC than the high-moisture walnuts. The IR pre-drying resulted in hot-air drying time savings of 22.69 percent for low-moisture walnuts and 17.05 percent for high-moisture walnuts.

Table 6: Hot-Air Parameters and Drying Time for the Walnut Drying With and Without IR Pre-drying (Test 1)

Walnut type	Bin	Air velocity, (m/s)	Hot air temp, °C	Drying time to 8% MC (min)	Drying time saving by IR drying (%)
Low	A5	0.58	42.4	1554	22.69
	A6	0.58	42.4	1685	

Walnut type	Bin	Air velocity, (m/s)	Hot air temp, °C	Drying time to 8% MC (min)	Drying time saving by IR drying (%)
Low IR	C4	0.60	40.1	1232	
	C5	0.60	40.3	1272	
High	D4	0.60	42.4	1400	17.05
	D5	0.60	43.8	1532	
High IR	B5	0.60	41.3	1112	
	B6	0.60	41.4	1320	

Energy consumption: For IR pre-drying, the major energy source is the natural gas consumed by the emitters. The natural gas consumed by the four sections of the IR dryer was measured from the flow meter in British Thermal Units per hour (BTU/h) for each section. The electrical energy used to operate the vibratory feeder and the four conveyors was calculated in kilowatts and calculated. For hot-air drying, the static pressure of hot air for each bin was measured in inches of water column. The air flow was calculated using the equation developed for walnut drying by Rumsey (1981).

$$V = 278.6\left(\frac{\Delta p}{h}\right)^{0.5446}$$

Where V is the velocity through walnuts (ft/min), Δp is the static pressure (inches of water column) and h is the height of walnuts in the bin (ft).

From the air velocity, hot-air temperature and dimensions of the bin, the energy used for hot-air drying of walnuts in each bin was calculated. The electrical energy consumed for operating the hot-air blower was calculated. The energy consumption of low- and high-moisture walnuts with and without IR pre-drying is shown in Table 7.

Table 7: Energy Consumption and Savings for Walnut Drying With and Without IR Pre-Drying (Test 1)

Walnut type	Bin	Drying time (min)	Hot air temp, C	HA energy, MJ	IR energy, MJ	El. energy, MJ	Total energy, MJ	Average Total Energy (MJ)	Energy Saving, %
Low	A5	1554	42.4	18711	0	932	19643.68	20471.64	19.94
	A6	1685	42.4	20289	0	1011	21299.61		
Low IR	C4	1232	40.1	13076	2228	758	16061.32	16388.65	
	C5	1272	40.3	13707	2228	782	16715.98		
High	D4	1400	42.4	17402	0	840	18242.35	19967.94	14.54
	D5	1532	43.8	20774	0	919	21693.54		
High IR	B5	1112	41.3	12835	2228	686	15748.49	17064.57	
	B6	1320	41.4	15342	2228	810	18380.65		

MJ = Megajoules

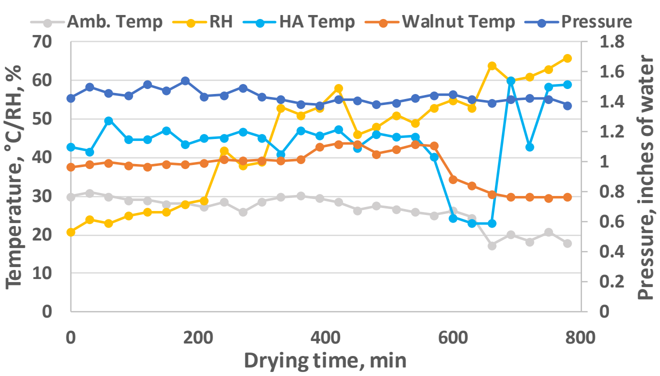
The results showed that IR drying consumed only 13.59 percent of total energy consumed for low-moisture walnuts and 13.05 percent of total energy consumed for high-moisture nuts. Comparing the energy consumption of IR pre-dried walnuts and without IR pre-dried walnuts, it was found that IR drying could save 14.54 percent to 19.94 percent of energy consumption.

Results for Test 2

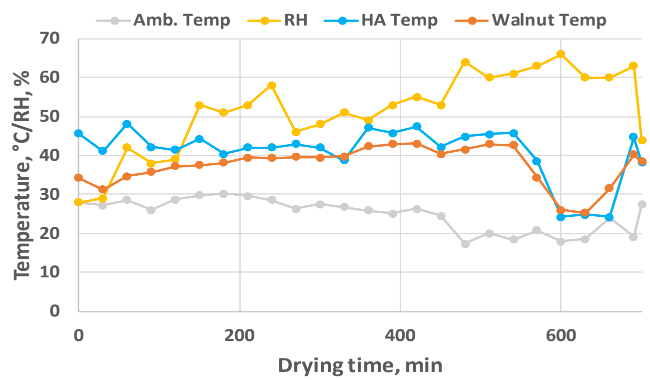
The hot-air dryer parameters, including the hot-air temperature, static pressure of hot air, ambient air temperature, relative humidity and walnut surface temperature, were all recorded for walnut drying tests conducted on September 30, 2016, and are shown in Figure 29 and Figure 30.

The average drying time, temperature of hot air and air-flow rate for the eight hot-air drying bins calculated from the recorded parameters for Test 2 are provided in Table 8. The table shows that the hot-air drying of IR pre-dried walnuts took a shorter time than that of walnuts without IR pre-drying for both high-and low-moisture walnuts, similar to the Test 1 results. The IR pre-drying resulted in hot-air drying time savings of 13.55 percent for low-moisture walnuts and 26.50 percent for high-moisture walnuts.

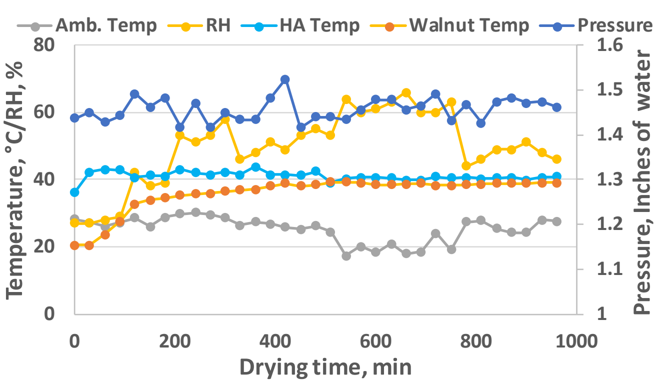
Figure 29: Hot-Air Parameters for High Moisture Nuts With and Without IR Pre-drying (Test 2)



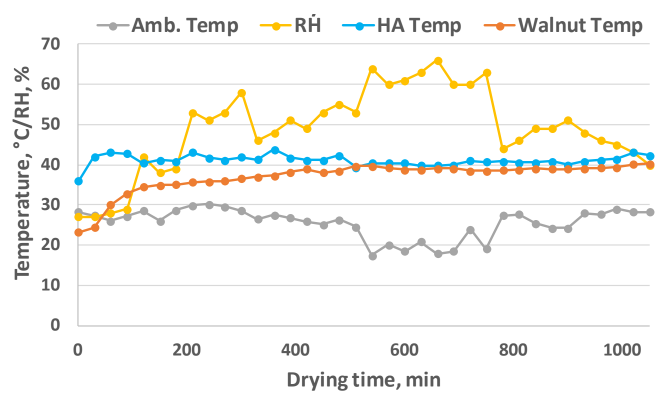
a. IR High moisture (Bin B5)



b. IR High moisture (Bin B6)

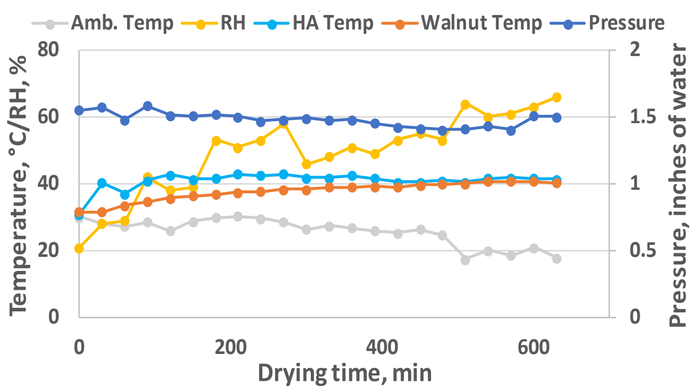


c. High moisture (Bin D4)

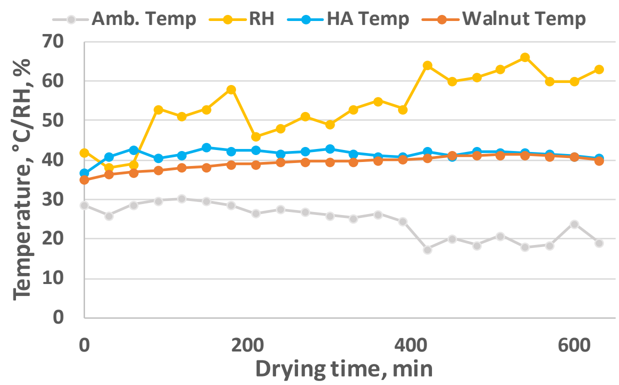


d. High moisture (Bin D5)

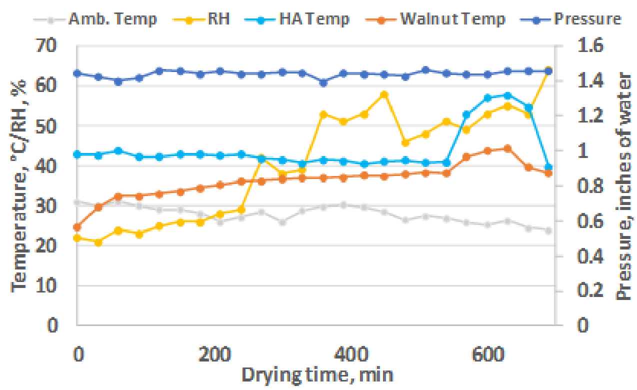
Figure 30: Hot-Air Parameters for Low-Moisture Nuts With and Without IR Pre-drying (Test 2)



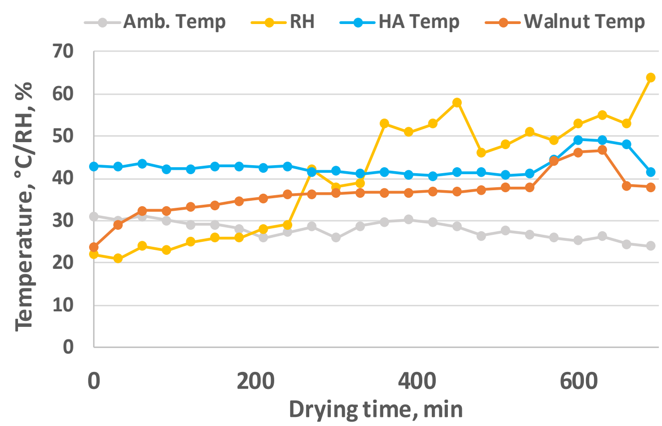
a. IR low moisture (Bin C4)



a. IR low moisture (Bin C5)



a. Low moisture (Bin A5)



a. Low moisture (Bin A6)

Table 8: Hot-Air Parameters and Drying Time for Walnut Drying With and Without IR Pre-dried Walnuts (Test 2)

Walnut type	Bin	Air velocity, (m/s)	Hot air temp, °C	Drying time to 8% MC (min)	Drying time saving by IR drying (%)
Low	A5	0.60	42	688	13.55
	A6	0.60	42	700	
Low IR	C4	0.60	39	617	
	C5	0.60	39	583	
High	D4	0.60	41	968	26.50
	D5	0.60	41	1051	
High IR	B5	0.60	40.5	783	
	B6	0.60	40.5	700	

Energy consumption: From the air velocity, hot-air temperature and dimensions of the bin, the energy used in hot-air drying of walnuts in each bin was calculated. The electrical energy consumed for operating the hot-air blower was calculated. The energy consumptions of low- and high-moisture walnuts with and without IR pre-drying are shown in Table 9.

Table 9: Energy Consumption and Savings for Walnut Drying With and Without IR Pre-Drying (Test 2)

Walnut type	Bin	Drying time (min)	Hot air temp, °C	HA energy, MJ	IR energy, MJ	El. energy, MJ	Total energy, MJ	Average Total Energy, MJ	Energy Saving, %
Low	A5	688	42	8997	0	413	9410	9492	9.96
	A6	700	42	9154	0	420	9574		
Low IR	C4	617	39	6619	1566	559	8744	8546	
	C5	583	39	6254	1566	528	8348		
High	D4	968	41	12044	0	581	12625	13166	13.90
	D5	1051	41	13077	0	631	13708		
High IR	B5	783	40.5	9317	1845	710	11872	11336	
	B6	700	40.5	8322	1845	634	10801		

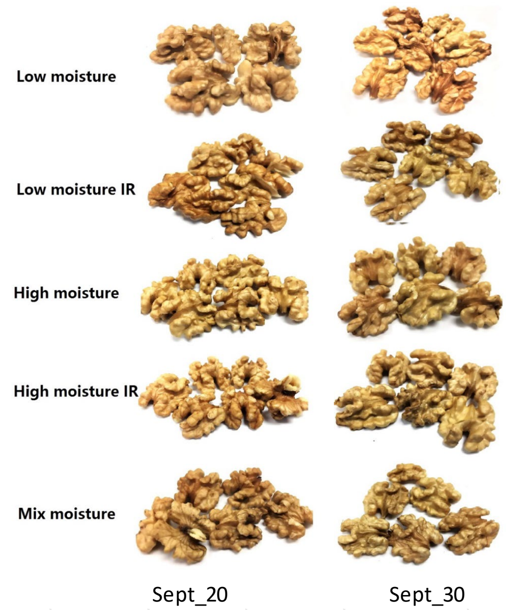
The results showed that the IR drying consumed only 18.32 percent of total energy consumed for low-moisture walnuts and 16.28 percent of total energy consumed for high-moisture nuts. Comparing the energy consumptions of IR pre-dried walnuts and without IR pre-dried walnuts, it was found that IR drying could save 9.96 percent to 13.90 percent of energy consumption.

Quality and Shelf Life of Walnuts

The effect of IR pre-drying on the quality of walnuts, including the color (lightness) of walnut kernels, PV, and FFA content of the walnut oil extracted from the walnut kernels, were determined for walnuts dried in Test 1 and Test 2. For comparison, the quality of walnuts dried without sorting and dried by hot air was used. An accelerated shelf life study was conducted to investigate the quality change in IR pre-dried walnuts when compared with hot-air dried walnuts.

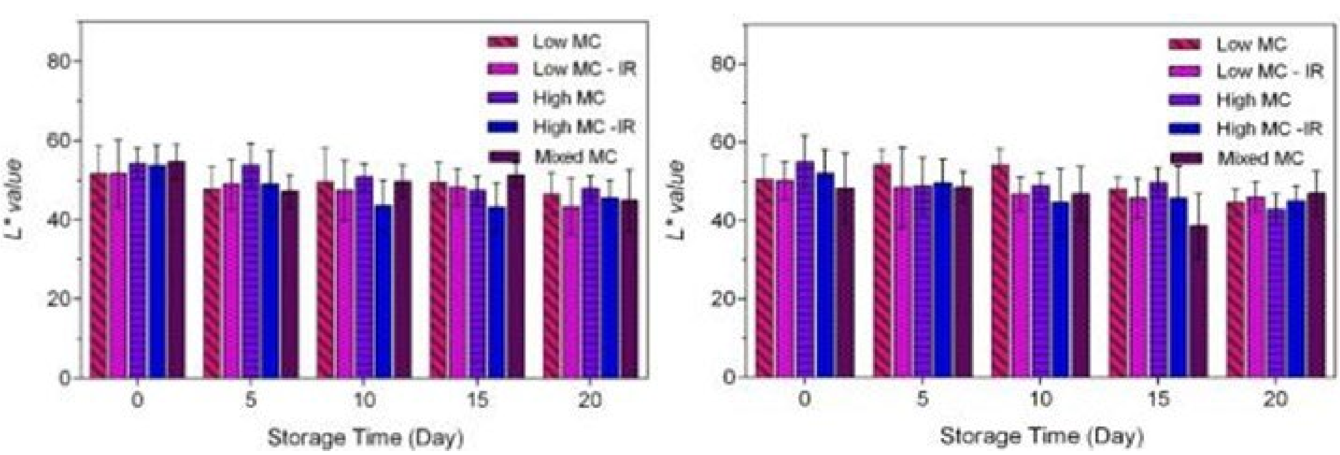
Color Lightness: The kernels extracted from the walnuts and used for color lightness (a*) measurement are shown in Figure 31. No visual color difference was observed.

Figure 31: Walnut Kernels With and Without IR Pre-Drying Treatment



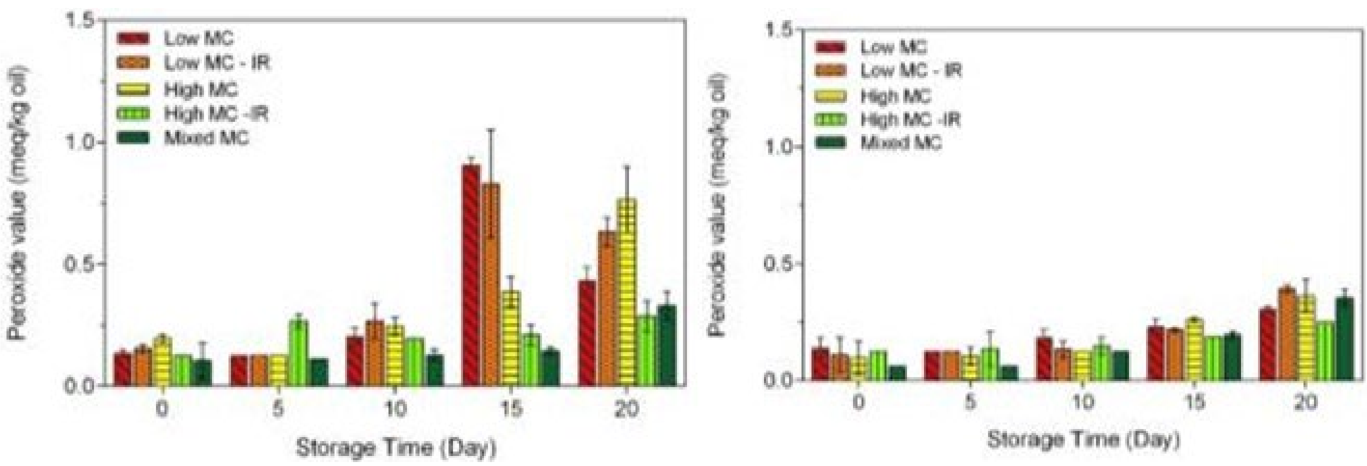
The color lightness values (L*) of all three tests showed that all the dried nuts, including the IR pre-dried walnuts (Figure 32), had a higher L* value than the industrial requirement (L* value of 40) even after the storage period of 20 days (2 years), except for the mixed (unsorted) walnuts from test 2 after 15 days of storage. This might be an experimental error as the color values of the same were above 40 after 20 days of storage. The color lightness value of IR pre-dried walnuts on day 0 for test 2 was lower than that of the hot air dried high moisture walnuts but it had a higher value than the L* value of mixed walnuts dried by hot air. The color lightness values from the commercial IR dryer confirms the test results of the pilot scale dryer, showing that IR pre-drying has no significant effect on the color of walnuts. The color values gradually reduced during storage, but all the treatments had a color value higher than the industry standard of 40.

Figure 32: Effect of Storage Time on L* Values (lightness) of IR Pre-Dried and Hot-Air Dried Walnuts for Test 1 (left) and Test 2 (right)



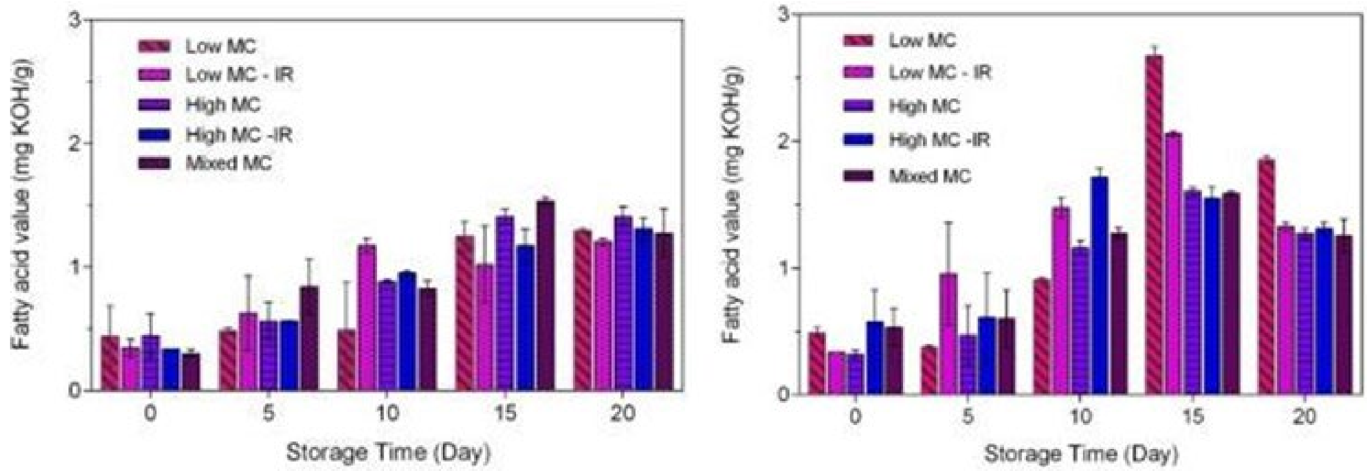
The peroxide values of all the walnut samples, with and without IR pre-drying, were less than 0.5 Meq/kg of oil, as shown in Figure 33. There was no definite trend in the change of PV values during the 12 months of storage for the walnuts tested on two days. However, after 18 months of storage, the PV values significantly increased for low-moisture nuts with and without IR drying for Test 1, whereas the increase was gradual for all walnuts for Test 2. Walnuts with a PV value of less than 1 Meq/kg of oil are considered safe for sale by the walnut industry, which means that the IR pre-dried walnuts could be stored for as long as two years without affecting the quality, as indicated by the color and PV values. No significant difference in the color lightness values (L*) and PV values of IR pre-dried walnuts and hot-air dried walnuts were observed during the storage period of 20 days.

Figure 33: Effect of Storage Time on PV of IR Pre-dried and Hot-Air Dried Walnuts for Test 1 (left) and Test 2 (right)



The FFA values for all the walnut samples of the two tests are shown in Figure 34. The FFA value of oils extracted from high-moisture IR dried walnuts were the highest (Test 2) followed by mixed walnuts. The results indicated that IR pretreatment had no negative effect on the FFA value of walnut oil. The FFA values gradually increased with storage time. FFA values less than 0.6 g/100g indicate acceptable walnut quality, as recommended by the walnut industry in California (Wang et al., 2007). The studies on quality and shelf life of IR pre-dried walnuts showed that there were no significant differences in the color lightness value (L*), PV and FFA values between IR pre-dried walnuts and hot-air dried walnuts observed during the storage period of 20 days. The IR pre-dried walnuts can be stored for about 6 months while maintaining the color, PV and FFA values stipulated by the state's walnut industry.

Figure 34: Effect of Storage Time on Free Fatty Acid Value of IR Pre-Dried and Hot-Air Dried IR Pre-Dried and Hot-Air Dried Walnuts for Test 1 (left) and Test 2 (right)



Conclusions

Two drying tests were conducted to evaluate the commercial scale IR walnut dryer during the walnut harvest season of 2016 at the Emerald Farms walnut drying facility in Maxwell, California. In the first test, high- and low-moisture walnuts of the Howard variety with moisture contents of 25.67 percent and 20.44 percent were heated in the IR pre-dryer for 210 s throughput capacities of 10.67 and 12.00 tph. The IR pre-drying of walnuts resulted in moisture removals of 5.19±0.41 percent and 3.10±0.71 percent and hot-air drying time reductions of 22.69 percent and 17.05 percent for the low- and high-moisture walnuts, respectively. IR pre-drying followed by hot-air drying resulted in energy savings of 19.94 percent and 14.54 percent for both low- and high-moisture walnuts, respectively, compared with hot-air drying alone. For the second test, walnuts with moisture contents of 17.34 percent (low moisture) and 22.83 percent (high moisture) were pre-dried in the IR dryer for 188 s and 225 s, producing an IR dryer capacity of 14.22 and 12.60 tph, respectively. IR pre-drying resulted in moisture removals of 3.62±0.65 percent and 3.96±0.53 percent and hot-air drying time reductions of 13.55 percent and 26.50 percent for the low- and high-moisture walnuts, respectively. IR pre-drying for 210 s, followed by hot-air drying, resulted in energy savings of 9.96 percent and 13.90 percent for low- and high-moisture walnuts, respectively, compared with hot-air drying alone.

Commercial scale IR walnut dryer test results showed that the IR pre-drying resulted in energy savings of 9.96 percent to 19.94 percent compared to hot-air dried walnuts without IR pre-drying, depending on the IR heating time and the initial moisture content of walnuts. The commercial scale IR dryer was not covered at the bottom, exposing the hot conveyor belt area of 768 square feet at 158°F (70°C) to wind speeds of 1-3 m/s at an average ambient temperature of 77°F (25°C). The heat loss to the air was estimated to be 10 to 15 percent. Placing a proper cover on the bottom of the conveyor to reduce the heat loss can further improve energy savings by 2-3 percent. As the unsorted (mixed) walnuts usually consume more energy than sorted walnuts, total energy savings from sorting and IR drying will be up to 25 percent, similar to the 2015 results. Therefore, it is concluded that the sorting of walnuts into low- and high-moisture nuts and IR pre-drying for 3-4 min could result in energy savings of up to 25 percent compared to hot-air drying of unsorted (mixed) walnuts. Quality and shelf-life studies of IR pre-dried walnuts showed that there was no significant difference in the color lightness value (L*), PV and FFA values between IR pre-dried walnuts and hot-air dried walnuts during the storage period of 20 days, under accelerated storage conditions. The IR pre-dried walnuts can be stored for about 6 months while maintaining the color, PV and FFA values stipulated by the industry.

CHAPTER 3: On-Site Demonstration of Infrared Walnut Dryer

The purpose of the on-site demonstration tests was to promote the adoption of new energy efficient walnut drying technology by showing the participants the significant reduction in consumption of natural gas and electricity; improved product quality; and reduced product loss, production cost, and air pollution in California. A related purpose was to collect feedback from interested parties from the walnut industry.

Three demonstration tests were carried out at Emerald Farms in Maxwell, California, in the walnut harvesting seasons of 2015 and 2016, with the pilot-scale IR walnut dryer and commercial-scale IR walnut dryer, respectively.

Demonstration of Pilot-Scale Infrared Walnut Dryer

A demonstration was arranged for the CEC project manager and her team on October 12, 2015, at Emerald Farms. They were taught about the design and operation of the IR dryer, as well as the experimental setup used to compare energy consumption of sorted and IR pre-dried walnuts with that of unsorted walnuts, to 8 percent MC (Figure 35).

Figure 35: Operation of IR Dryer (left) and Hot-Air Bin Dryer (right) at Emerald Farms in Maxwell, California

Operation shown to CEC team by Professor Pan

A demonstration was arranged on October 12, 2015, for the advisory committee members, and another demonstration for walnut growers and processors was arranged on October 13, 2015. The design and function of the IR dryer were presented, including details of the drying experiments and findings of the project including reductions in drying time, savings in natural gas and electricity consumption, quality improvements, and reductions in drying costs. The plan for building and testing the commercial scale IR dryer was explained and their inputs on the capacity and the conveyor dimensions were obtained.

Demonstration of Commercial-Scale Infrared Walnut Dryer

Demonstration of the commercial scale walnut dryer was conducted on October 4, 2016, for project managers from the California Energy Commission, walnut growers in California, and researchers from USDA and UC Davis. The total number of participants was 17. Prof. Pan provided a short presentation of the project, highlighting the background of the walnut drying process, energy consumption in walnut drying, objectives of the project, and expected outcomes. The demonstration of the commercial walnut IR dryer was conducted using the Chandler variety, and participants were given a short tour of Emerald Farm's drying facility where the operation of the IR dryer, hot-air dryer, and details of the drying experiments were explained. Participants discussed the benefits of the IR dryer, including drying time savings, energy savings, and nut quality with Emerald Farms owner Leon Etchepare.

Conclusions

To demonstrate and commercially implement the energy-efficient drying of walnuts, two infrared (IR) walnut dryers were designed, built, tested, and demonstrated during the walnut harvest seasons of 2015 and 2016. In 2015, a pilot scale infrared walnut dryer with a capacity of 1 tph was designed and built in collaboration with Wizard Manufacturing Inc., and tested at Emerald Farms in Maxwell, California. The hulled and washed walnuts were sorted into two moisture groups of low- and high-moisture walnuts, and the high-moisture walnuts were IR pre-dried to three different kernel temperatures of 104°F (40°C), 113°F (45°C), and 122°F (50°C) in the pilot scale IR dryer. The IR pre-dried walnuts were conveyed to the hot-air drying bins and dried to a moisture content of 8 percent. The nearby hot-air drying bins were filled with walnuts without IR drying and dried to 8 percent MC for comparison. The results showed that IR heating for 150, 180, and 240 s, respectively, resulted in walnut kernel temperatures of 104°F (40°C), 113°F (45°C), and 122°F (50°C), respectively. IR heating resulted in significant moisture removal from the walnut shell compared with the kernel. Energy consumption studies showed that sorting the walnuts into two moisture groups and drying them separately could save up to 28.80 percent of energy compared with drying the unsorted walnuts by preventing over-drying. The energy saved by IR pre-drying alone was found to be 11.68 percent, 12.81 percent, and 11.70 percent, with IR heating the walnuts to the kernel temperatures of 104°F (40°C), 113°F (45°C), and 122°F (50°C), respectively.

A commercial-scale IR walnut dryer with a capacity of 10-15 tph to IR pre-dry the walnuts by heating to a kernel temperature of 122°F (50°C) was designed, built, tested, and demonstrated in 2016. The throughput capacity of the IR dryer varied between 10.67 to 14.22 tph. The IR pre-drying resulted in moisture removal of 3.10±0.71 percent to 5.19±0.41 percent, depending upon initial moisture content, IR heating time, and kernel temperature obtained after IR heating. IR pre-drying of walnuts reduced the hot-air drying time by 13.55 percent to 26.50 percent compared with walnuts without IR pre-drying (with the same initial moisture content). IR pre-drying resulted in energy savings of 9.96 percent to 19.94 percent compared to walnuts dried without IR pre-drying, depending on IR heating times and initial moisture contents of the walnuts.

The pilot scale and commercial scale IR walnut driers were demonstrated to walnut processors, walnut growers, walnut drying equipment manufacturers, researchers, and extension workers from the nut industry, universities, and USDA. Considering the energy savings from sorting the walnuts and the projected energy savings by covering the IR dryer, it could be possible to save up to 25 percent of energy in walnut drying with IR pre-drying. Quality would not be sacrificed, as the IR pre-dried walnuts can be stored for about 6 months while maintaining the color, PV, and FFA values stipulated by California's walnut industry.

Dissemination of Project Results

The infrared drying technology of walnuts and its benefits to walnut quality, drying time reductions and energy savings were disseminated to fruit and vegetable processors and the consumers by poster presentations, demonstrations and videos at the UC Davis Picnic Day 2017 on April 22, 2017. The poster displayed at the UC Davis Picnic Day, shown in Figure 36.

Figure 36: UC Davis Picnic Day 2017 Poster Showing the Infrared Walnut Dryer

The IR drying of walnuts technology was demonstrated to participants of the California League of Food Processors (CLFP) Expo 2018 held on February 21-21, 2018, in Sacramento through poster displays, brochures, and videos (Figures 37 and 38). The technology was appreciated for its energy benefits including drying time reductions and energy savings (as indicated by visitor feedback).

Figure 37: Poster on IR Walnut Drying Displayed at CLFP Expo 2018

Figure 38: Brochure on IR Walnut Drying Distributed at CLFP Expo 2018

The results of this project were published in conference presentations and the following peer-reviewed journal publications.

- Wang, X., G.G. Atungulu, R. Khir, Z. Gao, Z. Pan, S.A. Wilson, G. Olatunde, and D. Slaughter. (Sorting In-Shell Walnuts by Using Near Infrared Spectroscopy for Improved Drying Efficiency and Product Quality (International Agricultural Engineering Journal, May 5, 2016).
- Pan, Z., R. Gebreil, C. Venkitasamy, B. Wang, H. Teh, J. Chen, I. Rabasa, and L. Pan. 2016, Effect of Pre-Sorting and Pre-Infrared Drying of Walnuts on Energy Saving. Presented at the Annual International Meeting of American Society of Agricultural and Biological Engineers (ASABE). July 17-20, 2016, in Orlando, Florida: oral presentation.
- Venkitasamy, C., C. Chen, Y. Shen, W. Zhang, R. Gebreil, H. El-Mashad, R. Zhang and Z. Pan. 2017. Design and Evaluation of Commercial Scale Infrared Walnut Dryer. Presented at the Annual International Meeting of ASABE, Jul 16-19, 2017 at Spokane, Washington.
- Venkitasamy, C., C. Chen, R. Gebreil, R. Zhang, Z. Pan. 2018. Effect of Infrared Pre-Drying of Walnuts on Saving Drying Time and Energy Use. Poster presented at the CLFP Food Processing Expo, February 21-22, 2018, Sacramento, California.

Next Steps

The project team from UC Davis and USDA-ARS will continue to disseminate the infrared drying of walnuts technology to California's walnut growers and processors. The project team will use various forums and expos organized by walnut growers such as the California Walnut Research Board, CLFP, and the UC Davis Picnic Day to meet walnut growers and disseminate results of the infrared walnut drying technology project and its benefits in terms of walnut quality, drying time reductions, and energy savings through posters, brochures, and videos. An infrared drying technology video is available on YouTube. https://www.youtube.com/watch?v=j0qx5FOhyjc and at the UC Davis website https://video.ucdavis.edu/media/t/0_emqs9dnz.

GLOSSARY AND LIST OF ACRONYMS

Term	Definition
ANOVA	analysis of variance
ARS	Agricultural Research Service
ASABE	American Society of Agricultural and Biological Engineers
Btu/h	British Thermal Units per hour
CEC	California Energy Commission
CIE	Commission Internationale de L'Esclairage
CLFP	California League of Food Processors
EHM	energy consumed by the sorted high-moisture nuts in kJ/ton
EIR	energy consumed by the sorted IR pre-dried nuts in kJ/ton
ELM	energy consumed by the sorted low-moisture nuts in kJ/ton
EMixed	energy consumed by the unsorted mixed walnuts in kJ/ton
FFA	free fatty acid
FIR	far infrared
HAD	hot air drying
IMC	initial moisture content
IR	infrared
kJ/ton	kilojoules per ton
L*	color lightness value
MC	moisture content
MIR	medium infrared
MJ	megajoules
NIR	near infrared
Δp	static pressure
PV	peroxide value
UC	University of California
USDA	United States Department of Agriculture
μm	micrometer

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