INFRARED PRE-DRYING AND DRY-DEHULLING OF WALNUTS FOR IMPROVED PROCESSING EFFICIENCY AND PRODUCT QUALITY

G. G. Atungulu, H. E. Teh, T. Wang, R. Fu, X. Wang, R. Khir, Z. Pan

ABSTRACT. *The walnut industry is faced with an urgent need to improve post-harvest processing efficiency, particularly drying and dehulling operations. This research investigated the feasibility of dry-dehulling and infrared (IR) pre-drying of walnuts for improved processing efficiency and dried product quality. Freshly harvested walnuts (ethephon and non-ethephon treated) with whole and partly-attached hulls were dehulled using a test device to determine dry-dehulling time and frequency. The physical dimensions of walnuts without, with partly-attached, and with whole hulls were determined. In-shell walnuts of high (43%, w.b.) and low (18%, w.b.) moisture were pre-dried with IR for 2, 3, and 4 min followed by hot air (HA) drying at 43°C for up to 24 h and effects on drying rate and product quality were studied. Based on results, walnuts with whole and partly-attached hulls could be dry-dehulled to achieve over 90% dehulled nut in 45 and 15 s, respectively. Ethephon treatment had no significant influence on dry-dehulling of walnuts with partly-attached hulls. Contrarily, Ethephon-treated walnuts with whole hulls had dehulled nut percentage higher than untreated ones. Walnuts without, with partly-attached, and with whole hulls could be separated based on axial dimensions. IR pre-drying improved walnut drying rate. Up to 7% moisture reduction for high moisture nuts was achievable in 240 s of IR pre-drying with nut center temperature relatively below 43°C in the first 150 s. IR pre-drying for 180 s followed by HA drying had no effect on the quality of processed products compared with HA. The studied approaches have potential to improve processing efficiency and quality of dried walnuts.*

Keywords. *Walnuts, Infrared pre-drying, Shelf life, Dry dehulling, Processing efficiency.*

Walnuts are rounded, single-seeded stone fruits of the walnut tree. The walnut fruit is enclosed in a green, leathery, fleshy hull. This hull is inedible. After harvest, the removal of the hull reveals the wrinkly walnut shell, which encloses the kernel. The seed kernel which is commonly available after processing as shelled walnuts is enclosed in a brown seed coat. There are several major problems related to processing cost, energy use, and product quality in the current postharvest processing of walnuts. Walnuts with-hulls are transported from orchards to drying site for dehulling and then the hulls must be transported away for disposal, which uses a significant amount of energy. Also, existing dryers commingle all nuts regardless of the large difference in moisture content (MC) of the nuts entering the drying process. The typical average moisture content of walnuts harvested with hull is about 33% compared to 14% for walnuts without hulls. The MC of the wetter nuts could be as high as 43% (Khir et al., 2013). To ensure the wet nuts achieve the safe storage moisture of 8% the dryer nuts are over dried which represents significant energy use and prolonged drying time (Thompson and Grant, 1992, Thomson et al., 1998). The current low air temperature drying at 43°C has low drying efficiency and limits the nut processing capacity. The walnut industry has a pressing need to develop new and cost effective walnut dehulling and drying methods which can improve energy efficiency, reduce negative environmental footprint and provide high quality processed products.

At harvest, walnuts with- and without-hull are collected from the ground with harvesters and then transported to a facility for dehulling and drying. Transporting walnuts with hull from orchards to drying site for dehulling and then the hulls away for disposal could be mitigated by introducing in-field dehulling practice. Typically, the hulls contain significant amount of moisture, 85% on average, and the transportation represents a significant amount of energy and labor wastages, as well as greenhouse gas emission (GGE) resulting from automobiles used in the transporta-

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tion. A new approach involving in-field dehulling could cut down the miles per year due to hauling thereby reducing GGEs. Moreover, in-field dehulling facilitates application of the hulls back into the orchard for long-term carbon sequestration and soil amendment. Cost effective and sustainable implementation of the in-field dehulling device would require dehulling the walnuts dry which is unlike the conventional wet dehulling device that soaks the walnuts in water before dehulling. At the same time, it would be vital to sort walnuts based on hull attachment conditions at harvest which includes walnuts without hull, walnut completely covered with hull, walnut with hull but not completely covered and sunburned walnuts. Our previous research (Khir et al., 2012) reports the feasibility of using either axial dimensions or aerodynamic methods for sorting walnuts with and without hull. In-field sorting would make it easy to implement in-field dehulling without soaking in water, also hereafter referred to as dry-dehulling.

In the typical walnut processing, after the dehulling step, the mixture of dehulled walnuts along with the nuts without-hull at harvest are conveyed together into a batch air dryer for drying typically using natural or propane gas at a 43°C air temperature. The drying time could be up to 24 h for the wettest nuts to achieve the safe storage moisture content of 8%. Presently, the average energy consumption for walnut drying is high with 12.16 therms of natural gas or propane (1.216 million BTU) and 23.6 kWh electricity used per ton of walnuts (http://coststudies.ucdavis.edu/files/huller-dryerstudy2009. pdf). The energy consumption during the drying could be dramatically reduced by introducing walnuts with more uniform moisture content into dryers, which can be achieved by size and pneumatic sorters (Khir et al., 2012, 2013). Our studies have demonstrated that at harvest the kernel and shell moisture are different but have a strong correlation (Khir et al., 2013). The shell MC averages of walnuts without hulls were 17.4%, 18.2%, and 15.6%, whereas the corresponding values for kernel MCs were 11.2%, 11.8%, and 8.8% for Tulare, Howard, and Chandler varieties, respectively. Walnuts shell surface heating with controlled high temperature without compromising the kernel quality could be useful to rapidly remove moisture, improve the drying rate, and thereby reduce gas and electricity used during walnut drying.

Based on drying theory, at relatively high initial MC, an initial linear reduction of the average product MC as a function of time may be observed for a limited time, often known as a constant drying rate period. Usually, in this period the surface moisture outside the product is removed. The drying rate during this period is dependent on the rate of heat transfer to the material being dried. Therefore, the maximum achievable drying rate is considered to be heat-transfer limited. Nuts with high initial moisture content may be dried at elevated temperatures during the first part of the drying process when rapid loss of moisture causes the kernel temperature to be significantly cooler than drying air temperature. The elevated temperatures could be used to drive out most of the moisture in the shell of high moisture containing nuts without affecting the product quality. Using a high temperature for partial drying followed by drying at a constant 43°C air temperature for sorted nuts based on their MC should reduce energy by minimizing the over-drying of walnuts.

IR radiation releases energy in electromagnetic wave form in the spectrum from 0.75 to 1000 μm. Principle food components, including water, organic compounds, and biological polymers, absorb IR radiative energy efficiently in the wavelengths ranging from 2.5 to 100 μm through the mechanism of changes in molecular vibration states, which corresponds to the medium- and far-IR regions. Hence, the medium- and far-IR radiations could be efficiently used for thermal processing of foodstuffs and agricultural products. Infrared heating achieves high and rapid heat flux to product surface in shorter times compared to hot air heating and therefore is appropriate for the initial drying. Sequential IR predrying and hot air drying is ideal to avoid product shrinkage due to steep moisture gradients as well as other physicochemical changes in quality. Especially, hot air drying in the falling-rate drying period, when the rate of removal of moisture from the interior of the product is a mass-transfer limiting process, would improve dried product quality rather using IR drying throughout. The industrial implementation could be to divert the wetter nuts to a high temperature continuous-flow dryer to be used for initial drying and the nuts would finish drying in an existing bin dryer at conventional drying air temperature. Another option would be to direct the wetter nuts to separate bins in the dryer. Bins for the high moisture nuts would be fitted with auxiliary heaters to increase air temperature above 43°C. Air temperature would be ramped down based on the average nut moisture measured by an in-bin moisture content sensor. A third implementation would be to dry the wetter nuts at 43°C.

The use of infrared (IR) drying or pre-heating for partial dehydration has been investigated as a potential method for reducing drying time, improving drying rate, and obtaining high quality dried food, including fruits, vegetables, and grains (Ginzburg, 1969; Abe and Afzal, 1997; Afzal and Abe, 1998; Hebbar and Rastogi, 2001; Zhu et al., 2002; Amaratunga et al., 2005; Pan et al., 2008; Pan and Atungulu, 2010a, 2010b). To the best of our knowledge, no studies have reported the application of IR to dry walnuts. However, a small number of literature has reported that walnuts could be dried with high air temperature for speeding up the walnut drying (Lowe et al., 1961; Sibbett et al., 1974; Thompson et al., 1985; Rumsey and Lu, 1991). IR may be used as a pre-drying method before hot air drying to heat the walnut quickly and remove a large amount of moisture from walnut shells within a short time, especially for walnuts with high initial MC.

Typically, walnuts contain 60% of lipids, predominantly made up of unsaturated fatty acids (Jensen et al., 2001; Wang et al., 2001) with double bonds, which make them very susceptible to oxidation reaction at high temperature. Peroxide value of walnut oil, which estimates the amount of peroxides generated during the first step of lipid oxidation reaction correlates to the status of oxidative rancidity in walnuts (Maté et al., 1996). It is vital that the IR heating temperature and time be controlled not to compromise product quality (Koyuncu et al., 2003).

The objectives of this research were to investigate the feasibility of dry-dehulling of walnuts and determine the impact of IR pre-drying of in-shell walnut on drying efficiency and dried product quality. The specific project objectives were as follows: (1) Determine the physical characteristics of walnuts with- and without-hull; (2) Investigate feasibility of dry-dehulling of walnuts; (3) Study the drying effectiveness and product quality with use of infrared heating (IR) for partial drying of walnuts.

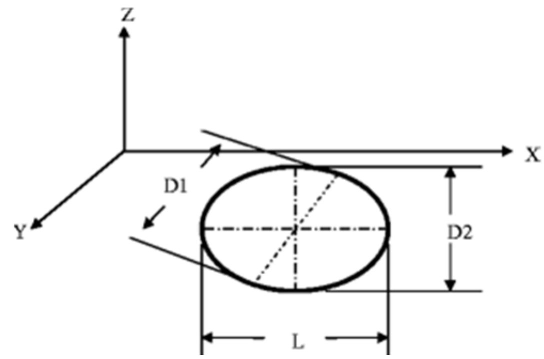


Figure 2. Three major axial dimensions of walnuts with and without hulls.

Materials and Methods

Determination of Physical Characteristic of Walnuts

Freshly harvested walnuts of Chandler variety were procured from Cilker Orchards (Dixon, Calif.) during the 2011 harvest season and used throughout this study. The samples treated with and without Ethephon were collected from the field or harvester. Typically, Ethephon treatment is used to accelerate hull opening after nut maturation so that the nut get drier before harvest. In this research, the obtained walnut samples were cleaned to remove trash and damaged, sunburned, and broken walnuts. The remaining nuts were divided into two categories namely with- and without-hulls. The nuts with hulls were further grouped into two categories including those with whole and partially-split hulls (fig. 1). Walnuts with partially-split hulls consisted of two categories of nuts including those with hull cover area of greater than 0% to <50% and those with hull cover area of 50% to < 100%.

The dimensions of the principal axes of walnuts with and without hull were determined. Major diameter (*L*) or length, intermediate diameter (D_1) or width, and minor diameter or thickness (D_2) of selected nuts with and without hulls were measured using an electronic digital caliper of 0.001 mm accuracy (fig. 2). The geometric mean diameter (D_g) in millimeters was determined by equation 1 (Mohsenin, 1980).

$$D_g = (L \times D_1 \times D_2)^{0.333} \qquad (1)$$

where

L = major diameter (mm)

D_1 = intermediate diameter (mm)

D_2 = minor diameter (mm)

Study of Dry-Dehulling of Walnut

A batch-type conventional vegetable dehulling device (Blakeslee, 60P207, Dallas, Tex.) was used to test the feasibility of dry-dehulling of walnuts (fig. 3). The dehulling device was comprised of a fixed support frame, a motor, a hull collector, a dehulling chamber, and a safety cover. The dehulling of nuts was accomplished majorly by impact of the nuts on a lining within the dehulling chamber. Freshly harvested walnuts of Chandler variety (ethephon and non-ethephon treated) with whole and partly-attached (>50% cover) hulls were used in the study. Feasibility to dehull the walnuts with the dehulling device was evaluated in terms of dry-dehulling time and frequency of walnut dehulled (percentage of dehulled walnuts). The batch capacity of the dehulling device throughout the tests was maintained at 3 kg of walnuts.

IR Pre-Drying of Walnuts

The infrared equipment set up used in the experiment is shown in figure 4a,b. Catalytic emitters provided by Catalytic Industrial Group (Independence, Kan.) were used as the IR radiation sources. The emitters generated IR radiation energy by catalyzing natural gas to produce heat along with very small amounts of water vapor and carbon dioxide as by-products. The dimensions of the emitter length and width were 60×30 cm. The feasibility of using infrared (IR) pre-drying to quickly remove part of walnut shell moisture before low temperature air drying at 43°C and the temperature profile within walnut during IR pre-drying and were studied. Freshly harvested walnuts with

Whole Hull Attached | **Partially Attached Hull (hull cover 0 to <50% and >50 to <100%** | **Without Hull Attached**

Figure 1. Different categories of walnut hull conditions at harvest: nuts without hulls, with whole hulls and with partially attached hulls.

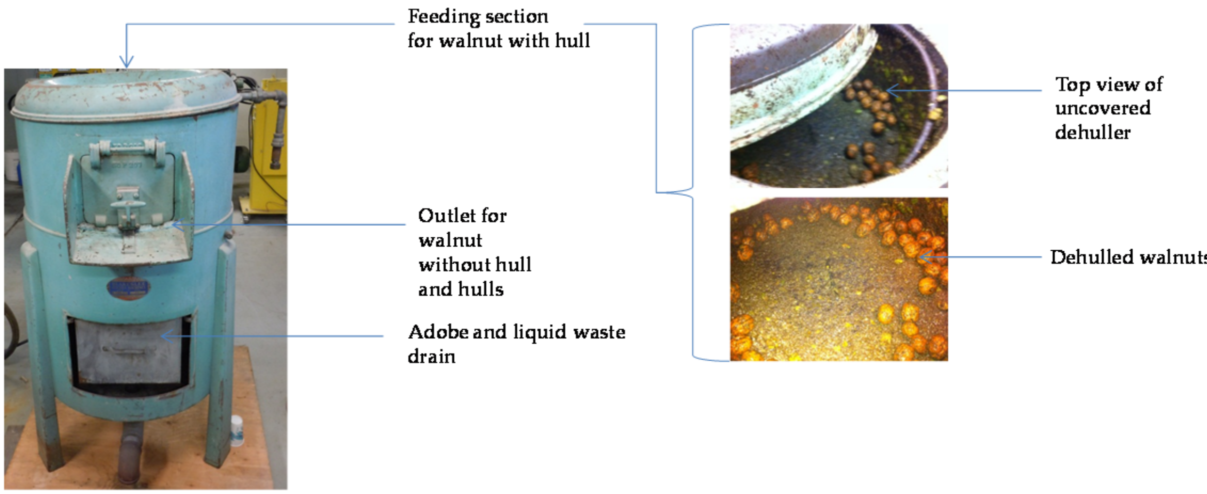


Figure 3. A batch-type conventional dehulling device for testing feasibility of dry-dehulling of walnuts.

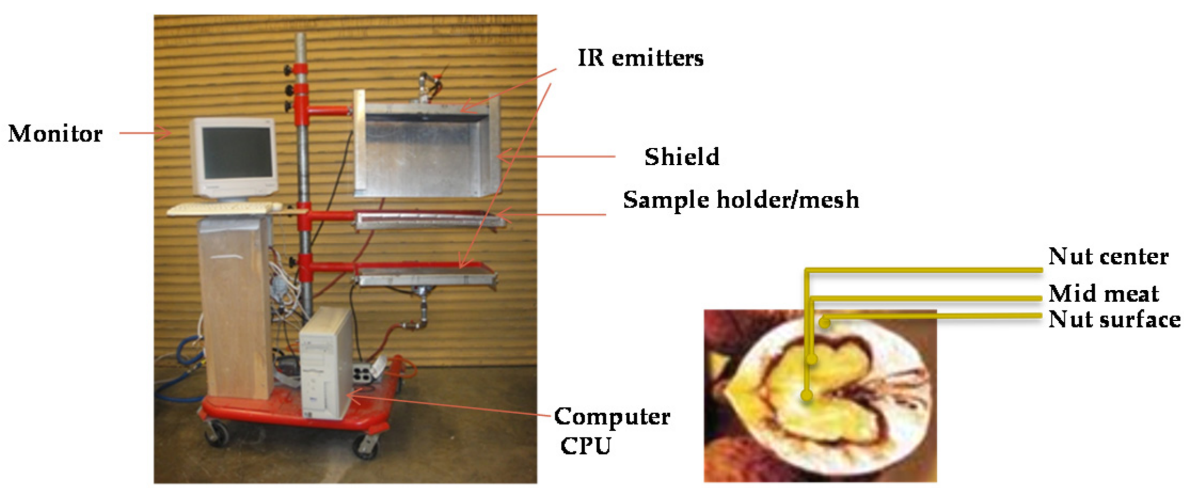
high (43.3±3.1% w.b.) and low (17.4±1.0% w.b.) average initial moisture contents (MCs) were used in the study. The high moisture nuts were procured from a local orchard (Dixon, Calif.) with hull attached, then dehulled and kept in plastic bags at a low temperature (4°C) until use. The low moisture nuts were procured without hull attached and similarly kept in plastic bags at low temperature (4°C) until use. To conduct IR pre-drying, the selected walnuts were placed equidistantly in a single layer between two catalytic IR emitters, spaced 25 cm apart and at surface temperatures of about 400°C, and then heated for 2, 3, and 4 min followed by conventional low temperature air drying at 43°C for up to 24 h. Also, the temperature profile during IR pre-drying was determined using T-type thermocouples placed at various locations including nut surface, mid meat, and center points of the walnut (fig. 4b). The reported surface temperature profiles are averages of triplicate experiments.

Moisture Content Determination

The walnut hull was manually removed from nuts harvested with hull. The kernel was extracted from each nut using a manual nutcracker. The shells and kernels (10g each) were separately placed in tare aluminum dishes and weighed using an electronic balance (Denver Instrument, Arvada, Colo.) with an accuracy of 0.01 g. Based on our preliminary tests to determine the MC of walnuts and their components we found that walnut samples reached a constant dry weight after 24 h at 100 °C in the air oven. Therefore, the components were dried in a hot air oven at 100°C for 24 h (Khir et al., 2013). Dried samples were removed from the oven, cooled in a desiccator and then reweighed. MC was determined for the shells, kernels and whole nuts based on the initial and final (dry) sample weights with at least five replicates conducted in each measurement.

Walnut Shelf Life Study

After low temperature air drying of the walnuts, accelerated shelf life studies were conducted over a storage period of 40 days at 35°C and 43.1% relative humidity. During storage, the walnuts were kept in a paper bag to prevent moisture build-up and mold growth. The storage conditions simulated approximately 4-year storage period



(a) (b)

Figure 4. (a) Infrared equipment set up and (b) location of temperature profile measurement within the walnut.

at 4°C according to a Q10 value of 3.4 at 35°C (Wang et al., 2006). The Q10 value is a ratio that related to the reduction of shelf life with storage temperature when the temperature is increased by 10°C. Walnut samples were collected after 0, 20, and 40 days of incubation, which corresponded to 0, 2, and 4 years of storage at 4°C. Quality attributes including nut surface color, moisture loss, and peroxide value of oil extracted from the nut were analyzed. The nut surface color was measured by using Minolta colorimeter (CR-200, Osaka, Japan) and the Commission International de l'Esclairage (CIE) *L*, *a*, and *b* color indices determined. The total color difference (ΔE), a single value which takes into account the differences between the *L*, *a,* and *b* of the sample and standard, was calculated from the following equation 2:

$$\Delta E = \sqrt{\left(L - L_o\right)^2 + \left(a - a_o\right)^2 + \left(b - b_o\right)^2} \quad (2)$$

where *L*, *a* and *b* are measured values and L_o, a_o, and b_o are standard values of the instrument.

Walnut oil extraction was accomplished using hexane as solvent. Five walnut samples were cracked, and the meat ground into powder with a kitchen blender (Ninja, Euro-Pro Operating LLC, Newton, Mass.). Weighted walnut and ten-time volume of hexane were added into a 500 mL beaker, and the mixtures were stirred with a stirrer bar at room temperature and in dark for an hour. The mixtures were then centrifuged at 5000 g at 4°C for 5 min to remove any walnut solids. Hexane was removed from oil and hexane mixtures using a rotary evaporator (Rotavapor model 461, Büchi, Switzerland) at 30°C. The oil was weighed and stored in 15 mL centrifuge tube at -20°C until further analyses. Peroxide value of the walnut oil was determined by the official method (Cd8-53) of the American Oil Chemists Society (AOCS, 1998).

DATA ANALYSIS

All data represents average of at least three replicates. Statistical analysis and multiple comparisons of significant differences at 0.05 level were conducted using SPSS software (SPSS Inc., Chicago, Ill.).

RESULTS AND DISCUSSIONS

SIZE DISTRIBUTION FOR IN-FIELD SORTING

The results showed that the axial dimensions including L, D_1, and D_2 of walnuts with hulls were greater than those of walnuts without hulls as expected. For example, the *L* ranged between 45 and 61 mm for walnuts with hulls and between and 35 and 45 mm for walnuts without hulls (fig. 5a). The D_1 ranged between 40 and 57 mm for walnuts with hulls and between 31 and 39 mm for walnuts without hulls (fig. 5c). The D_2 ranged between 37 and 51 mm for walnuts with hulls and between 28 and 38 mm for walnuts without hulls (fig. 5b). Additionally, the results of geometric mean diameter (D_g) distributions indicated that the D_g values of nuts with hulls were greater than those of nuts without hulls (fig. 5d).

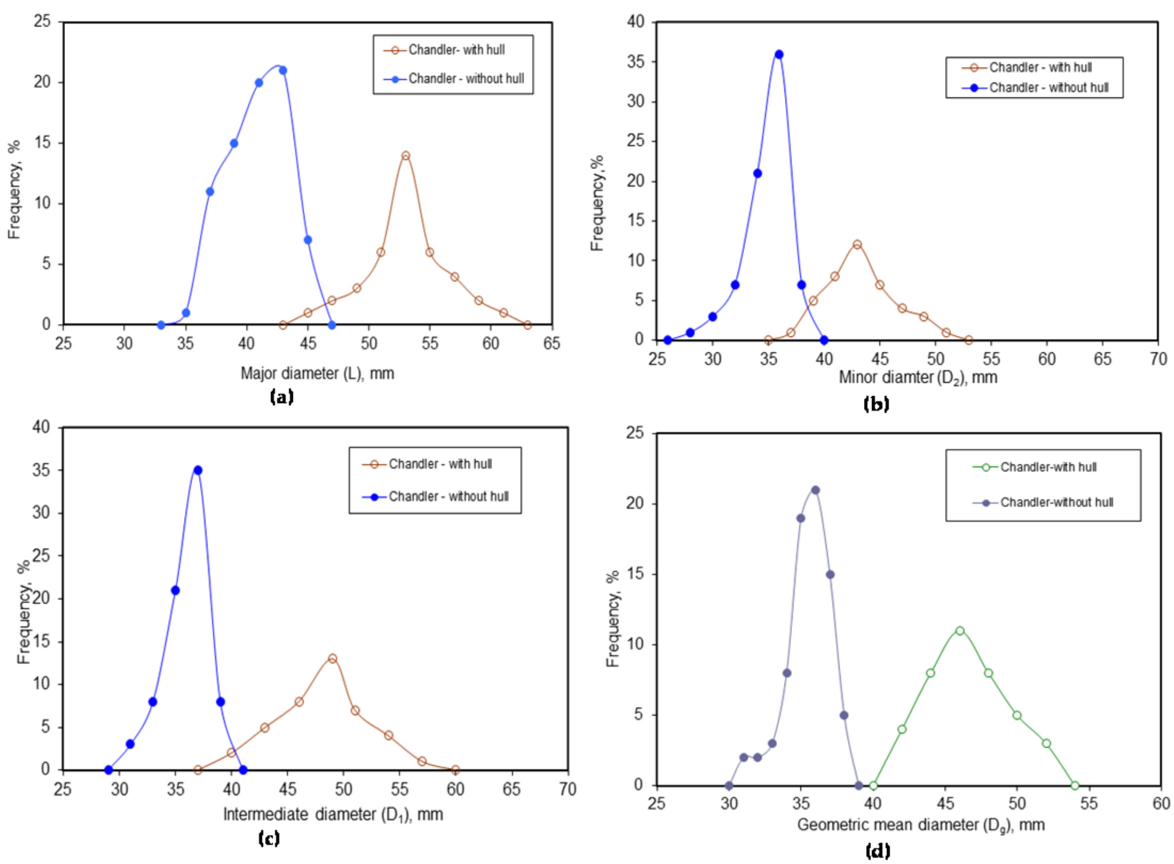


Figure 5. Size distribution of walnuts with and without hull attached.

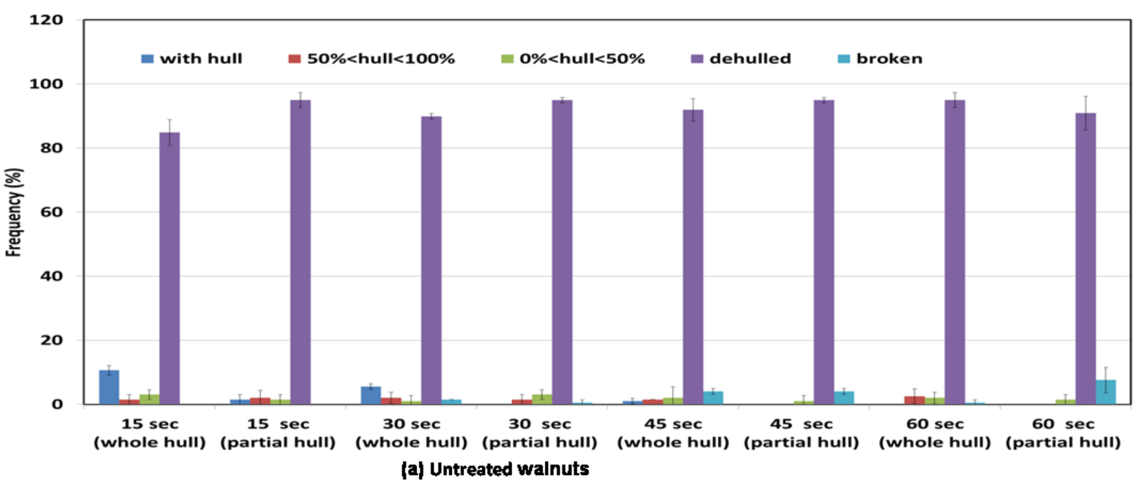
The above results showed that there are differences in nut size characteristics including axial dimensions and geometric mean diameters for nuts with and without hulls. There were overlapping regions of L, D_1, and D_2 of walnuts with and without hulls. This means that in designing sorting devices the overlap has to be considered to allow for minimum amount of walnut without hull that end up with those with hull or vice versa. There was a clear delineation in dimension characteristics when the geometric mean diameters of walnut with and without hull were considered. The two categories of walnut with and without hull could be distinctly classified based on the geometric mean diameter.

Although using the geometric mean diameter provides the best clear cut criteria for classifying the two groups of walnuts with and without hulls, it is practical and industrially easier to adopt the minor diameter (D_2) to design equipment for the separation. However, when the minor diameter is used, some small portion of walnuts without hull remains in the lot of walnuts with hull due to size overlap. Practically, this mixed portion can be conveyed to a dehulling device and later separated again based on moisture content. The size sorting based on physical dimensions could be an effective method for separating walnuts with and without hulls to facilitate in-field dehulling and also segregation of nuts based on difference in MC. Overall, the results suggested that it is feasible to separate walnuts based on size characteristics.

Effectiveness of Dry Dehulling

Based on findings of this research, both ethephon treated and untreated walnuts of chandler variety could be dry-dehulled. Figure 6 shows the frequency (%) of walnut samples dehulled, partially dehulled, not dehulled, or broken. The results indicated that walnuts with whole hulls generally took longer time to completely remove the hull than walnuts with partly attached hull. The suitable dry-dehulling times for walnuts with whole and partly attached hulls were 45 s and 15 s, respectively. Figure 6 also includes the dehulling frequency of sunburned walnuts. As expected, sunburned walnuts had lower dehulling efficacy.

Ethephon treatment slightly influenced the dehulling of nuts with hulls partly attached. However, in the case of nuts with hull intact, it was observed that ethephon treatment significantly influenced dehulled nut percentage, especially of nuts dehulled at 15 and 60 s. In general, higher dehulled nut percentage was attainable for nuts with hulls partly attached than with whole hulls. At 45 s, the dry-dehulled nut percentages of untreated and treated walnuts with whole hulls were 90% and 80% while those of nuts with hulls partly attached were 95% and 90%, respectively.



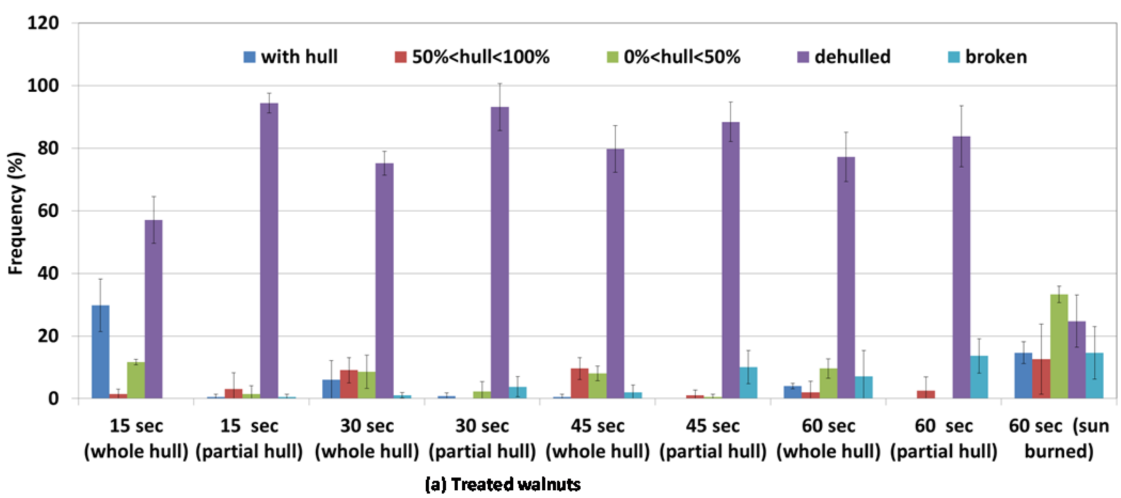


Figure 6. Dry dehulling of (a) ethephon treated and (b) untreated walnut with whole and partial hull attachments.

Although, the high dry-dehulling percentage of walnuts with hull partly attached was at 30 s, walnuts with hulls partly attached could also be dry-dehulled nearly at the same dehulling percentage in 15 s but with few broken or not hulled nuts. Overall, the findings successfully demonstrated the feasibility of dry-dehulling of walnuts.

IR Pre-Drying of Walnuts

Conventional drying of walnuts maintains the meat temperature at 43°C to retain product quality. Figure 7 shows the temperature profiles within a walnut during IR pre-drying. It was observed that a longer IR heating time is required for high moisture nuts to attain nut meat center temperature of 43°C compared to low moisture nuts. During IR pre-drying of the high moisture nuts, the nut center temperature remained considerably below 43°C in the first 2.5 min. After 4 min of IR heating the center temperature of the high moisture nut was about 80°C while that of the low moisture nut was 100°C. IR pre-drying might be effective for high moisture nuts since the meat temperature remains lower for a longer time than in the case of low moisture nuts.

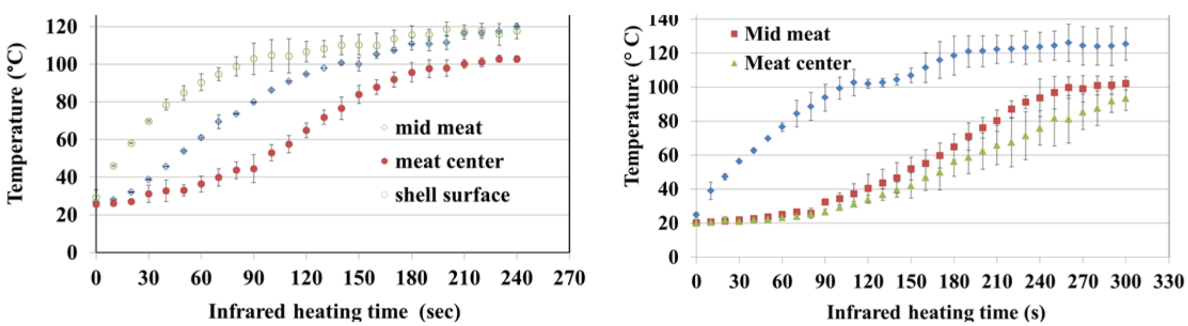
It was also observed that after 5 min of IR pre-heating, the low moisture nuts had burned surfaces. Whereas the high moisture nuts did not have burning after 5 min, instead they had developed surface cracks. Figure 8 shows the surface characteristics of high and low moisture walnuts during zero min to 5 min of IR pre-drying. Arrows in figure 8c indicate the typical locations of crack formation in walnuts heated with IR for 5 min. Based on these observations, limiting IR pre-drying time to 4 min or less was suitable without compromising the surface characteristics of the nuts.

Table 1 shows moisture reduction percentages by infrared pre-drying of both high and low moisture nuts. As expected, more moisture could be removed from high moisture nuts by IR pre-drying compared to low moisture nuts. For instance, up to 7.3% moisture reduction was achieved with 4 min IR pre-drying of high moisture nuts compared to 2.5% moisture reduction for low moisture nuts pre-dried with IR for the same time duration. Evidently, IR pre-drying could be used to remove a significant amount of moisture from the nuts prior to conventional low temperature drying at 43°C.

The effect of IR pre-drying of low and high moisture walnuts on low temperature drying is shown in figure 9. In the first phase of the falling rate drying period, especially when the drying potential was still high, it was observed that IR pre-drying of high moisture nuts for 3 and 4 min

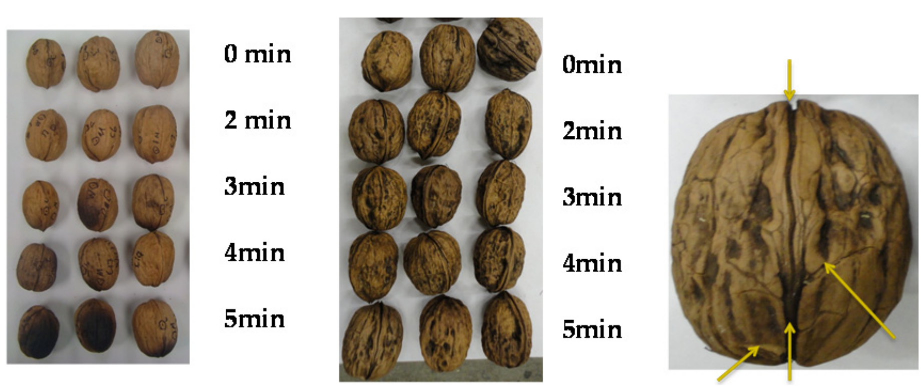
Table 1. Reduction of moisture content of walnut dried with infrared heating.

Infrared Heating Time (min)	Moisture Reduction (% d.b.)	
	Chandler High Moisture	Chandler Low Moisture
2	3.7±0.1	1.3±0.1
3	4.4±0. 7	1.9±0.1
4	7.3±2.0	2.5±0.3



(a) Low moisture nuts **(b) High moisture nuts**

Figure 7. Temperature profile with low and high moisture walnuts during IR pre-drying.



(a) Low moisture (17.4%, w.b.) **(b) High moisture (43.3%, w.b.)** **(c) High moisture nut cracking**

Figure 8. Effect of IR pre-heating on surface characteristics of low and high moisture walnuts.

reduced significant amount of moisture which was equivalent to a savings of 1 and 3 h drying time compared to control (fig. 9). It was observed that the amount of walnut moisture reduction by IR pre-drying of low moisture nuts was smaller than in case of high moisture nuts when they were subjected to similar IR treatments. This means that although some energy saving could be attained when low moisture nuts are pre-dried with IR, the amount of energy saving is comparably lower.

Walnuts Shelf Life Studies

Peroxide Value

Following IR pre-drying, the nuts were dried with conventional low temperature air at 43°C and shelf life studies were performed. The initial peroxide values (PV) of oils extracted from low moisture walnuts pre-dried with 2 min, 3 min, 4 min IR treatment, and control (not treated with IR) were 0.90±0.14, 0.33±0.15, 0.60±0.20, and 0.43±0.32 meq peroxide/kg oil, respectively (fig. 10). A PV value that is greater than 1.0 meq/kg is directly correlated to the onset of oxidative rancidity and exceeds the standards of acceptable quality of shelled walnuts according to the walnuts industry (Wang et al., 2001; Buransompob et al., 2003). On day 20, the peroxide values for 3 and 4 min treatments increased to 1.20 and 1.23 meq/kg oil, which exceeded the value normally acceptable by consumers. Except for oil extracted from walnuts pre-dried with IR for 3 and 4 min, the rest of walnut oils samples retained PV value not exceeding 1.0 meq/kg on day 40. Wang et al. (2006) also observed similar peroxide value changes for in-shell walnuts treated with 27 MHz radio frequency for 3 min. The results were also consistent with another study that reported the induction period for walnuts, stored at 37°C and in high oxygen environment, occurred around after 28 days of storage (Maté et al., 1996). There were no significant differences among the PVs of IR treated walnuts and untreated walnuts on day 0 and day 20 at significant level, $p \leq 0.05$. However, on day 40, the PV increased considerably with the 4-min IR treatment depicting substantially higher value as compared to 2 min, 3 min treatments, and controls. Peroxide values for the oils extracted from high moisture walnuts are shown in figure 11. The initial peroxide values were 0.69±0.30, 0.63±0.38, 0.53±0.25, and 0.85±0.66 meq peroxide/kg oil for 2 min, 3 min, 4 min IR treatments, and no treatment. All the oil samples, except for the control, surpassed 1.0 meq/kg oil on day 20. However, decreases in peroxide values were observed for 2 and 3 min oil samples on day 40. This occurred because the peroxides started to decompose to secondary oxidation products, such as hexanal and pentanal. A similar trend was reported by Jensen et al. (2001) in their study of quality change in walnut kernels stored at either 5°C or 21°C under light or dark condition. No significant differences were observed for the PVs of IR treated and untreated walnuts on day 0 and day 20. Again, the 4 min treated walnuts showed noticeably high peroxide value compared to walnuts from shorter treatment time and controls. The reason for the high peroxide value was because the 4 min treatment meant longer exposure time to heat which could compromise the product oxidative stability.

Surface Color of Walnuts

During storage of the nuts, there was no significant change in nut color characteristics. Table 2 shows the corresponding overall shell color changes (ΔE). Based on ANOVA, no statistical difference ($p \geq 0.05$) was observed in overall shell color of low and high moisture nuts pre-dried with IR at different times. However, based on multiple comparison results, the individual color characteristics of the walnuts (L, a, b) of low moisture had some correlations with storage time. The L, a, and b values of low moisture nuts at day zero and day 40 were significantly different ($p \leq 0.05$). While for high moisture walnuts a and b values indicated no significant difference ($p \geq 0.05$) for the studied storage duration, the L values were significantly different only for day zero and day 40 of storage. Based on the experimental results, it can be concluded that, overall, there was no significant effect of IR pre-drying on the color of the nut shell during the storage period. This means IR pre-drying could be carried out without affecting the marketability of in-shell walnuts post storage.

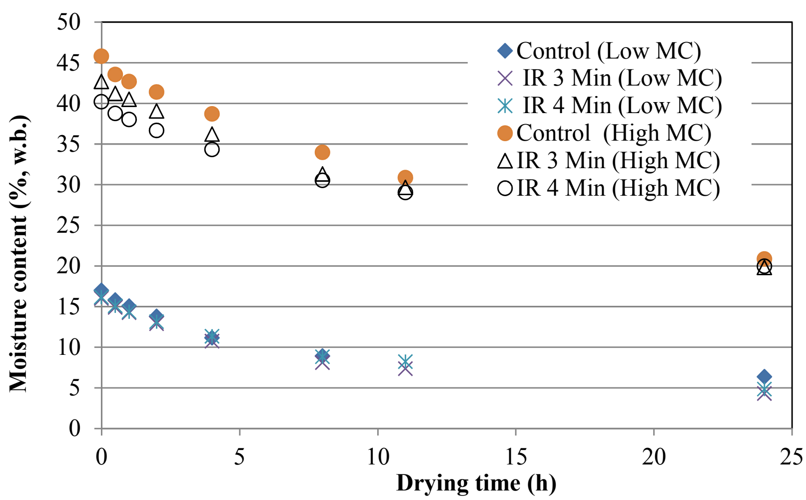


Figure 9. Effect of IR pre-drying of low and high moisture walnuts on low temperature drying time.

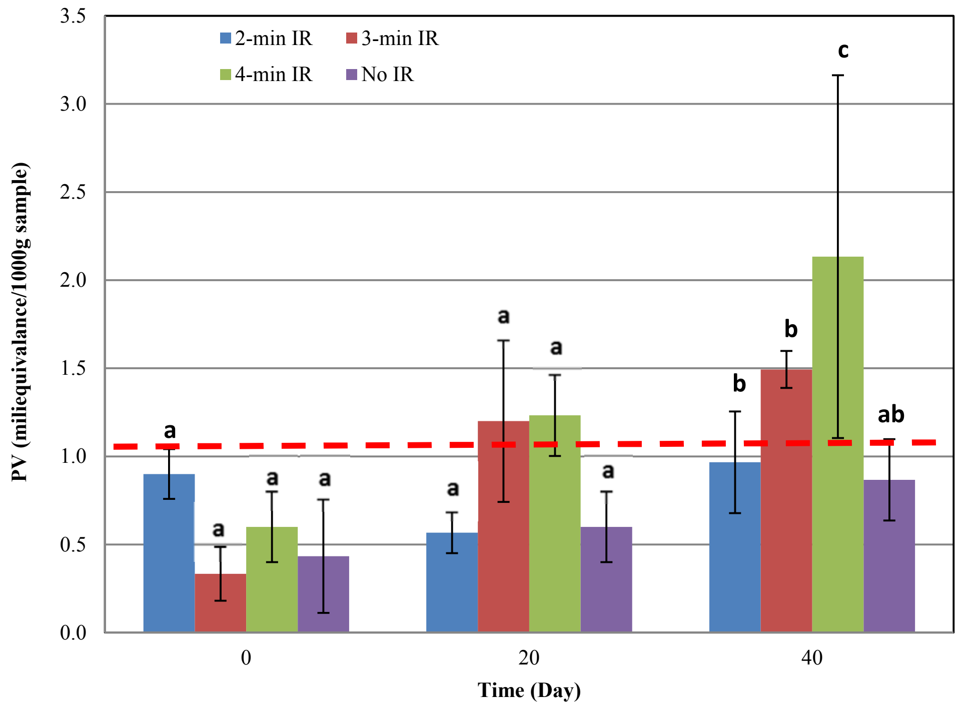


Figure 10. Peroxide values for IR-treated and untreated low moisture walnuts.

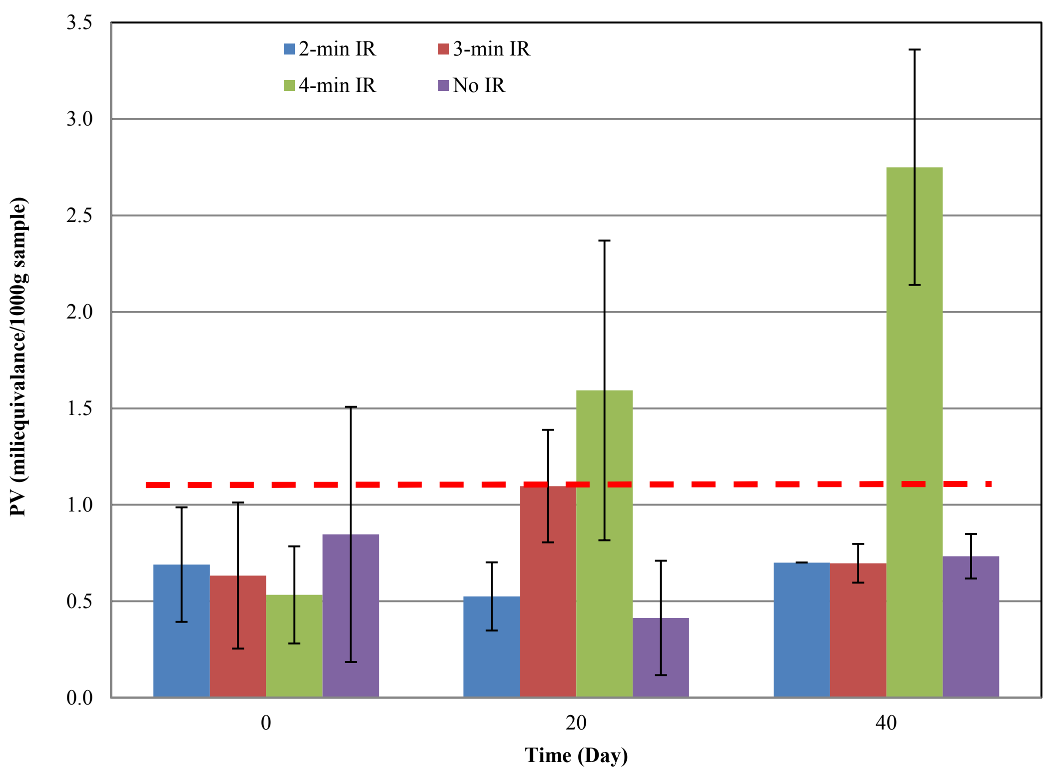


Figure 11. Peroxide value for IR treated and untreated high moisture walnuts.

Table 2. Color changes (ΔE) for IR pre-dried high and low moisture of the surface of in-shell walnuts.

Initial Moisture Content Category	Treatment time (min)	Color Change (ΔE) Time (Day) 0	20	40
Low	2	53.55±0.21	50.41±0.27	50.20±0.13
	3	54.49±0.86	51.38±1.33	50.97±0.63
	4	54.72±1.14	51.20±1.83	50.92±1.07
	Control	54.39±0.25	50.69±0.48	50.74±0.57
High	2	65.78±0.88	62.16±1.09	63.10±1.19
	3	65.59±0.36	62.03±0.32	62.86±0.17
	4	66.08±0.60	62.50±0.69	63.66±0.61
	Control	66.65±0.92	62.78±0.76	63.57±0.59

Conclusion

The study revealed that there are differences in nut size characteristics including axial dimensions and geometric mean diameters for nuts with and without hulls. Therefore, it is feasible to separate walnuts based on size characteristics, which could effectively enable practical separation of walnuts with and without hulls for in-field dehulling. The suitable dry-dehulling times for walnuts with whole and partly attached hulls were 45 and 15 s. Ethephon treatment influenced dehulling of walnuts with whole hull. However, no significant effect of Ethephon treatment was observed for walnuts with partly attached hulls. It was observed that IR pre-drying resulted in more moisture reduction of high moisture nuts (43%, w.b.) compared to low moisture nuts (18%, w.b.). Up to 7% and 2% moisture reduction could result from high and low moisture nuts respectively when IR pre-drying for 4 min was conducted before conventional drying at 43°C. IR pre-drying of high moisture nuts for 3 and 4 min reduced significant amount of moisture which translated to 1 and 3 h of the conventional low temperature drying time. During IR pre-drying of the high moisture nuts, the temperature of the meat at center of the nut remained considerably below 43°C in the first 150 s which provided time to drive out significant amount of moisture and also retained product quality. It took shorter IR heating times of 90 s to raise the meat temperature above 43°C at the center of the low moisture nut. IR pre-drying of high and low moisture nuts for 3 min followed by low temperature air drying had no significant impact on stored product peroxide value and color compared to controls. Based on overall product appearance and shelf life studies, IR partial drying time of 3 min is recommended before low temperature air drying of walnuts. Overall, the studied new approaches hold great promises in improving processing efficiency without affecting quality of walnuts.

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