Horticulture Innovation Australia

Final Report

Ultrasonic drying of horticultural food products

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Summary

Project objectives & Target audience

The Australian prune industry commissioned a three year research project to help maintain its sustainability and competitiveness through the application of ultrasound technology to enhance the drying process of plums for an efficient and cost-effective production of high quality dried products. This work builds on from the CSIRO's preliminary investigations on the application of ultrasound (i.e., as a treatment prior or during drying) to intensify low temperature drying of food materials. The present study was undertaken to understand, explore and optimise the application of ultrasound technology with the main focus to demonstrate its technological feasibility as a pretreatment to enhance the gentle (i.e., low temperature) drying of plums.

Project activities

The research project was conducted utilising fresh plum samples harvested from three consecutive seasons, from 2013-15. The project aims to establish the effects of ultrasound-based pretreatment at different pretreatment and drying parameters on the drying process and product quality attributes. A CSIRO computer-based experimental drying system was modified to suit the drying experiments of plums under controlled conditions over a wide range of operating parameters. Two sets of ultrasonic setup were developed and used for the ultrasound pretreatment of fresh fruit samples in an aqueous solution.

A suite of laboratory experiments were conducted for the 2013 and 2014 fruit harvest seasons to investigate the effects of ultrasound pretreatment parameters under various drying conditions on the drying performance (i.e., drying kinetics & time) and product quality attributes (i.e., colour, microstructure, antioxidant capacity, vitamin C). The pretreatment experiments were carried out at various parameters including pretreatment combinations, ultrasonic frequencies, sonication times and emulsion recycling. The impacts of ultrasonic pretreatments in enhancing the drying process were investigated under a matrix of drying conditions (i.e., temperature, relative humidity & airflow).

A number of experiments for the 2014 fruit harvest season were further carried out to demonstrate the scalability of the best pretreatment and drying conditions (i.e., established in previous experiments), and the impact of such large scale experiments on the rehydrability and pitting of dried plums at commercial scale conditions, and the corresponding changes on quality attributes (i.e., colour & antioxidant capacity). A number of laboratory experiments were also conducted for the 2015 fruit harvest season to investigate the effect of the best pretreatment conditions on the drying process. This was done under simulated dynamically changing drying conditions, typical in industrial tunnel drying of plums both in the counter-flow and parallel-flow modes of operation to demonstrate the effectiveness of the approach under commercial drying conditions.

Key outputs

A total of five milestone reports were submitted over the course of the project. In addition, a progress report was submitted and published in the prune industry advisory committee HIA's 2013/14 annual report. An article detailing the findings and progress of the project was also published in an industry-based Journal (The Vine: The Bi-Monthly Journal for the Australian Table Grape and Dried Fruits Industries, Jan/Feb 2015). The findings from this research were presented at the industry's annual

conference in 2014 to provide a forum for discussion to assess the direction and activities of the project. Ultimately, the main output of this project was the delivery of the final report, together with the development of the experimental prototype of the ultrasonic-based pretreatment and drying systems.

Key outcomes (results, consequences or impacts)

The results from this study showed that ultrasound-based pretreatment is effective in enhancing the drying process of plums with better product quality. Under the conditions investigated, the combination of ultrasound and oil emulsion pretreatment was found to have the highest effect in terms of intensifying the drying process compared to just ultrasound or oil emulsion pretreatments. The findings from the proof of concept experiments indicate that the ultrasonic oil emulsion pretreatment significantly reduced the overall drying time by up to 57% compared to samples dried without pretreatment, with better retention of the antioxidant capacity and vitamin C and lighter colour of the pretreated dried samples. The reduction of the overall drying time as a result of ultrasonic-based pretreatment is dependent on drying conditions and ultrasonic parameters.

The combined ultrasonic and oil emulsion pretreatment to enhance the drying process is more pronounced at lower drying temperature and progressively decreases with increase in drying temperature regardless of the air relative humidity. For example, plum drying with the application of pretreatment at 60°C resulted in 52% (about 22 hours) reduction in the overall drying time compared to 28% (about 4 hours) and 13% (about 1 hour) reduction at 70°C and 80°C drying temperature, respectively. This indicates that faster drying rates (i.e., resulting in increased throughput and reduced energy consumption with better quality of the product) can be achieved with the application of pretreatment at lower drying temperatures. The observed significant enhancement of the drying process is consistent with the reduced resistance to moisture transfer across the waxy skin layer of the fruit as a consequence of disrupting this layer by the pretreatment, demonstrated in the scanning electron microscopy (SEM) micrographs showing a thoroughly disorganised microstructure of the waxy skin surface layer.

The results from this work also unveil the impact of various process parameters of the ultrasound-based oil emulsion pretreatment on the drying process. There was only a marginal effect of ultrasonic frequencies under the conditions investigated in terms of reducing the drying time, with plums pretreated at 40 kHz were dried slightly faster than those plums pretreated at 270 kHz. On the other hand, no significant differences in the drying time between samples pretreated for 1 min and 5 min were observed. The samples pretreated for 10 min showed a slightly shorter drying time compared with the samples pretreated with the other two sonication times. This finding suggests that an effective pretreatment is possible with a shorter pretreatment time which is ideal for an industrial scale operation that requires a larger throughput to be commercially viable. Results also showed that the oil emulsion pretreatment solution can be reused for at least 3 times with no significant increase in drying time, providing a further cost saving avenue with the use of the oil emulsion pretreatment.

Results from the large scale experiments showed a 60% (about 25 hours) reduction in the overall drying time of plums pretreated with ultrasound oil emulsion in comparison with the non-pretreated plums dried at 60°C. This is consistent with the findings from the small scale experiments, suggesting the scalability of the process. No significant differences in the pitting efficiency between the non-pretreated and the pretreated samples were observed. In addition, the pretreated samples were found to have a lighter colour with higher antioxidant activity level (~33% more) compared with the non-pretreated samples, corroborating the results from the small scale experiments. Moreover, the findings from this work have also shown the effectiveness of the ultrasound oil emulsion pretreatment in enhancing the drying process under the dynamically changing drying conditions, typical in industrial scale operations for both parallel-flow and counter-flow tunnel configurations, suggesting the applicability of the approach in the commercial practice. It further shows that the effect of pretreatment is dependent on the levels of drying air velocity and progressively decreases as the drying temperature increases, consistent with the results found under constant drying conditions (small scale experiments). In addition, the findings reveal that the ultrasound-based oil emulsion pretreatment is effective in enhancing the drying process under the simulated commercial drying conditions regardless of the amount of wax presents in the fruit surface (i.e., fruit harvested at various time periods and seasons).

Recommendations (for future R&D and practical application to industry)

This research has demonstrated that ultrasound-based pretreatment is a highly effective means of enhancing low temperature drying of plums resulting in shorter drying time and better retention of product quality attributes. This offers a promising and superior alternative to current plum drying practice for efficient and cost-effective processing and safe operation to produce premium quality product. It is therefore recommended that the industry builds upon the outcomes of this research in bringing the new ultrasound-based pretreatment concept to industrial scale operations. The commercial practice of washing fresh fruit with ambient water prior to drying would provide a relatively easy way to incorporate the pretreatment procedure into the current commercial operations with minimum disruption. However, there are still technological challenges to overcome in order to strengthen its application and fully realise the successful adoption of the technology in industrial practice.

- Development of a design concept and building a pilot prototype of the ultrasound-based pretreatment technology for proof of concept testing and optimisation in commercial operations and techno-economic (cost-benefit) evaluation of the technology to assess its scalability and viability for commercial readiness
- Explore the potential of eco-friendly and cost effective approaches for a sustainable low temperature drying of plums (e.g., using solar drying technology) and the integration with the ultrasound-based pretreatment technology for drying intensification
- Study the changes on the quality attributes (i.e., rehydrability & pitting efficiency, antioxidant capacity, vitamin C, colour, etc) of the ultrasound-based pretreated dried plums during long storage (i.e., under the storage conditions typical in commercial practice)

The findings from the recommended further work would provide a strong basis for the successful development and implementation of the ultrasound-based pretreatment technology at industrial scale operations, enhancing the profitability and long term sustainability of the Australian dried prune industry. It is also anticipated that the pretreatment approach could easily be applied to enhance the drying process of other fruits and vegetables having waxy skin layer (e.g., grapes, berries, peas, tomatoes, etc), providing further benefits to other horticultural industries.

Keywords

Ultrasound; drying; oil emulsion pretreatment; plums; low temperature drying; drying intensification

Introduction

Background

Dried plum (or prune) is one of the important products for the dried fruit industry with worldwide production in excess of 275,000 metric tons in 2014 (IPA, 2015). It is widely consumed for its nutritional value including high dietary fibre content, antioxidants and its effectiveness in enhancement of digestive function. The industrial production of dried plums usually relies on drying of high-moisture fresh plums in long dehydration tunnels down to 20–24% final moisture content (Sabarez and Price, 1999). The drying process of plums is energy-intensive and slow, taking a long time to complete (up to 35 h, depending on the drying conditions) (Sabarez, 2010).

The slow process of drying plums is due to their skin layer having a cuticle coated with hydrophobic waxes, which represents an efficient barrier to water movement during drying. Price et al., (2000) have observed significant disruption of the structure of the waxy skin layer by SEM technique of plums dried at 70°C and above, which significantly increases the permeability of the skin layer to moisture transfer during drying. Thus, the resistance offered by the waxy skin layer to moisture transfer can be minimised by utilising higher drying temperatures (above 70°C) to accelerate the drying process. However, for most foodstuffs caution is required because higher temperatures may alter their physical and chemical constituents, which affect the quality of the dried product. Hence, the use of higher drying temperatures is limited to a point below which the undesirable characteristics are minimised. Also, increases in temperature would generally mean an increase in energy input requirement.

In Australia, the cost of drying plums accounts for a major portion of the total production costs (up to 50%) depending on the dehydrator design, drying conditions, type of fuel used, fruit size, among other factors (Sabarez, 2012; Sabarez, 2010). This is primarily due to the fruit's exposure to high temperatures or long drying times. There is significant interest in the industry to develop innovative approaches that will accelerate the drying process at low temperatures, thereby increasing throughput, and reducing energy consumption without compromising the quality of dried products. Previous studies have shown that the moisture diffusivity of the skin layer of waxy fruits can be improved by chemical (Bain and McBean, 1967; Sabarez, 1998; Doymaz, 2004) and physical (Jazini and Hatamipour, 2010; Cinquanta, 2002) pretreatments. The main challenge is to develop a sustainable and eco-friendly approach that enhances the drying process at low temperature.

Significance for the industry

A research project was commissioned to assist the Australian prune industry in enhancing profitability and competitiveness through the development of a novel approach that will reduce energy consumption, lower greenhouse gas emissions, increase production throughput and produce better quality dried products. This work was envisaged to contribute to addressing the emerging global challenges (i.e., food security, climate change) concerning the long term sustainability of horticultural industries, particularly as we move towards a carbon-reduced economy and to demonstrate the feasibility of the new approach that would have multiple benefits (i.e., economics, environmental, social).

Overall objectives

The project builds on CSIRO's preliminary investigations on the application of ultrasound (i.e., as a treatment prior or during drying) to intensify low temperature drying of food materials. The present study was undertaken to understand, explore and optimise the application of ultrasound technology through experimental studies, with the main focus to demonstrate its technological feasibility as a pretreatment to enhance the gentle (i.e., low temperature) drying of plums. This research was carried out to provide new insights into the mechanisms underlying the transport phenomena and the associated quality changes with the application of ultrasound-based pretreatment in drying of plums.

Linkages to previous projects

The application of ultrasonics would provide a more energy efficient drying process with better retention of product nutritional and functional properties as the process permits the use of low temperature while still potentially achieving faster drying rates. CSIRO has undertaken preliminary investigation of a novel concept based on the application of ultrasonics as a pretreatment or in combination with the conventional drying method, which has the potential to enhance the drying process in a sustainable and environmentally-friendly manner. The approach has been shown to significantly reduce the drying time by as much as 50% depending on product properties and process conditions (Sabarez et al., 2012). Similarly, other studies have shown the potential of power ultrasound to improve the drying process of fruits and vegetables (Garcia-Perez et al., 2007, 2009 & 2010; Gallego-Juarez et al., 1999; Carcel et al., 2007). However, no commercial-scale installation of the ultrasound drying technology has been developed to date (Soria and Villameil, 2010).

Methodology

Materials

Fresh plums obtained from the industry collaborators in Cobram (Victoria) and Darlington Point (NSW) were used in the laboratory drying experiments. Average sized fruits weighing between 10 and 20 g, were utilised. Fruit samples from three seasons (2013, 2014 and 2015) were used in this study. Samples were kept in sealed bags and stored of up to 3 weeks (Sabarez, 2010) in a cool store at 4°C prior to the drying experiments.

Moisture Content Determination

The initial moisture content of the fruit samples was determined using a standard AOAC method (AOAC, 1995) by vacuum drying over magnesium perchlorate desiccant (Sabarez and Price, 1999). In this method, 5 to 10g of ground sample was spread in an aluminum moisture dish and dried in a vacuum oven at 70°C for 6 hours under reduced pressure (<100mm Hg). This was repeated at least three times to obtain a representative average. The initial moisture content was expressed on a wet basis (kg H_2O/kg wet sample).

Experimental Setup

A computer-based experimental drying system was further developed and modified to suit the drying experiments of plums over a wider range of controlled operating conditions (Figure 1). The purpose-built test drying facility incorporated a number of special features including a fully programmable cyclic control of process conditions (i.e., temperature, humidity, and airflow), and a dedicated weighing system. The setup was equipped with controllers to control the process variables. The programmable feature of the process conditions of the experimental drying system allows one to study and simulate the drying process conditions typical in industrial scale operation (i.e., products subjected to dynamically varying drying conditions at any time and location in the drying system). A great advantage of this experimental setup is that it is equipped with a number of additional sensors (i.e., thermocouples, infrared noncontact temperature sensors, air velocity sensors, humidity sensors, etc.) that are interfaced to a computer-based data acquisition and control system for continuous online monitoring and recording of the various processing conditions (i.e., drying time, material temperatures, air temperature, air relative humidity, air velocity).

In addition, a removable airborne ultrasonic unit can be retrofitted into the experimental drying setup to study the influence of airborne ultrasound on the convective drying process under controlled conditions. The details of the experimental drying setup can be found elsewhere (Sabarez et al., 2012; Sabarez, 2012; Beck et al., 2014; Sabarez, 2014). The ultrasonic unit retrofitted in the experimental drying setup was developed by Gallego-Juarez et al., (2007). It consisted of a piezoelectric transducer (working at 20 kHz) with a rectangular flexural-vibrating plate driven by an electronic generator. The ultrasonic generator with a maximum power capacity of about 100 W was composed of a resonant frequency control system, a power amplifier, and an impedance adapter. A number of parameters of the driving signal applied to the transducer (frequency, voltage, current, and phase) were interfaced to the monitoring and control system of the dryer. Operation of the integrated drying facility was automatically performed using a PC with a specific application software developed in CitectSCADA version 6.0 (Schneider Electric, Rueil-Malmaison, France) to enable monitoring, supervision, and control of all process variables. This also allowed easy access to the process data (both real-time and historical) for decision making and further analysis.

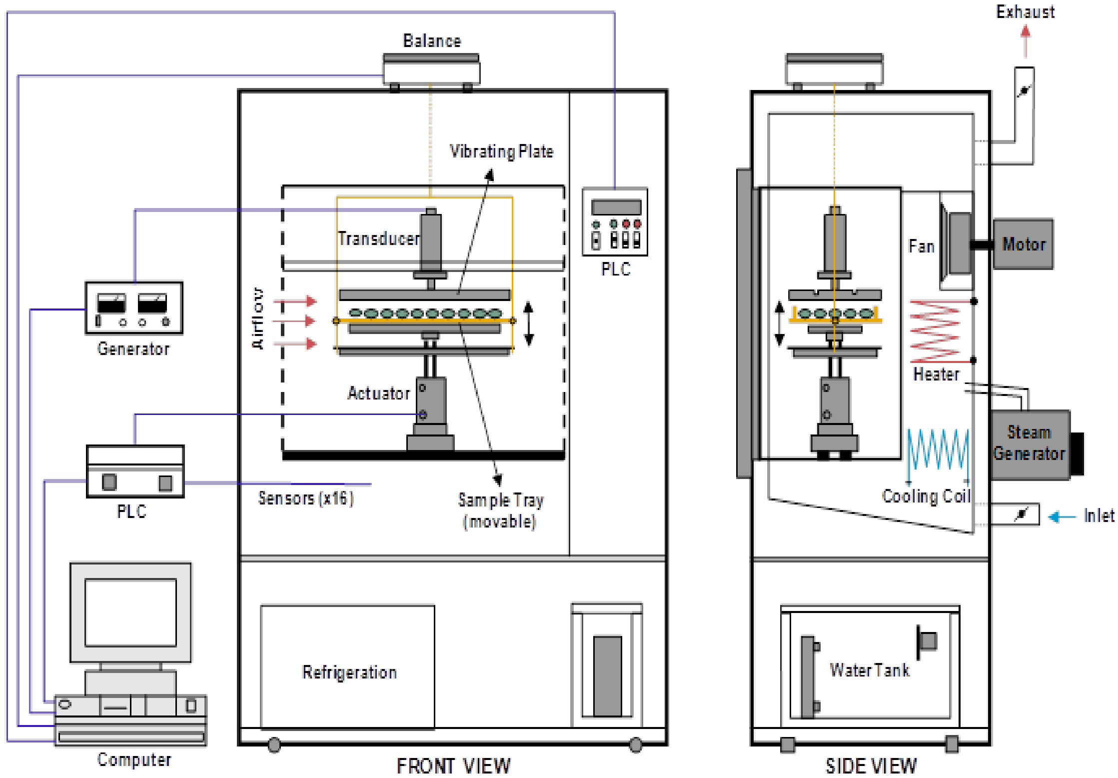


Figure 1. Schematic diagram of the experimental drying system.

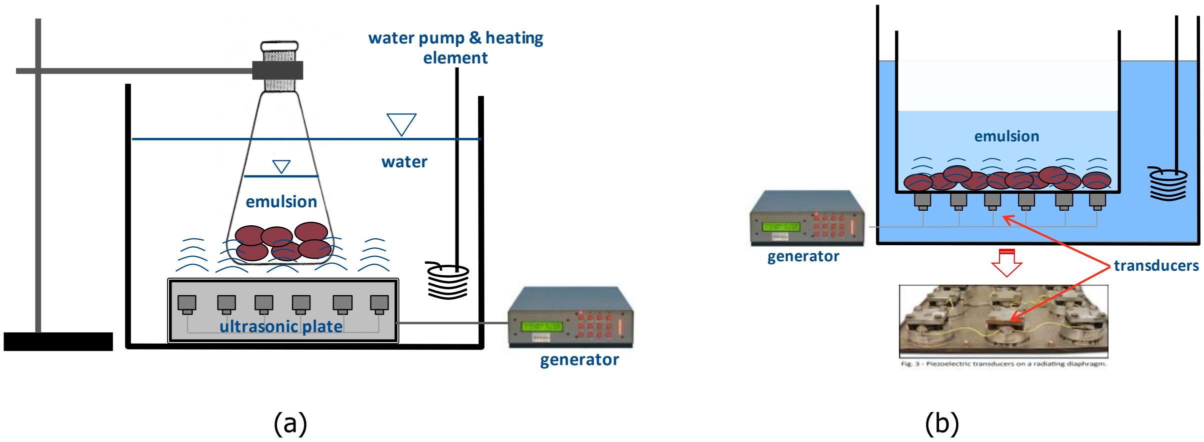


Figure 2. Schematic diagrams of the two ultrasonic pretreatment setups, (a) for small scale experiments and (b) for large scale experiments.

Two sets of ultrasonic setups were developed and used for the ultrasound pretreatment of fresh plum samples in an aqueous solution prior to drying. For small scale experiments, the ultrasonic pretreatment was carried out using a Blackstone-Ney Ultrasonics, MultiSONIK-2™ 7 frequency, Ultrasonic Generator (Blackstone-Ney Ultrasonics Inc., Jamestown, New York, USA, 900 cm^2 flat transducer plate, programmable duty cycle, adjustable output power and frequency) (Figure 2a). The ultrasonic power and frequency levels can be adjusted in the range of 0-100% and 40-270 kHz, respectively. The removable ultrasonic transducer is immersed into a water bath coupled to a temperature controller (Ratek, Melbourne, Australia) with a water recirculation system. For large scale experiments, the ultrasonic pretreatments were carried out using a Branson 8300 series ultrasonic tank (Branson Ultrasonics Corporation, USA) as illustrated in Figure 2b. The ultrasonic unit can be operated at 40 kHz with adjustable power levels (0-100%).

Pretreatment Procedure

The effects of various pretreatment combinations, including (a) non-pretreatment (dipping in tap water), (b) ultrasound and oil emulsion, (c) ultrasound in tap water only, and (d) oil emulsion only (no ultrasound) were the main parameters investigated using the small scale ultrasonic pretreatment setup. In this setup, fresh fruit samples (~150g per treatment) were added into a 1000 mL conical flask filled with 600 mL of aqueous oil emulsion and were pretreated at various pretreatment parameters. The aqueous oil emulsion was prepared by adding 2% (w/v) of either oil (ethyl oleate, olive oil & coconut oil) in tap water. Pretreatment experiments were carried out at various ultrasonic pretreatment parameters including power levels, frequencies, sonication times and emulsion recycling. The experiments were carried out at ultrasonic frequencies of 40 and 270 kHz, sonication times of 1, 5, & 10 minutes, and re-using of the emulsion solution of up to 3 times. For large scale and simulated industrial drying experiments, pretreatments were carried out using the best pretreatment combinations established in a series of small scale experiments. All pretreatment experiments were carried out at 25°C.

Drying Procedure

<u>Small scale drying experiments</u>

A series of preliminary short drying experiments (i.e., normally up to 5 hours) were carried out to initially assess and screen the impact of a range of process variables at different levels. Depending on the drying conditions, it would normally take of up to 40 hours to complete one drying cycle for plums. In addition, fresh plums are only available for 3-4 weeks in a year and usually won't last long under cold storage conditions. Therefore, the screening approach employed in this work has provided the ability to maximise the number of experiments that were undertaken. A similar approach has been reported in a number of drying studies that can be found in the literature (Newman et al., 1996; Sabarez, 1998).

A suite of laboratory drying experiments were conducted for the 2013 and 2014 fruit harvest seasons to investigate and explore the effect of ultrasound-based pretreatment on the drying process and product quality attributes. In these experiments, the final moisture content of 20% wet basis was set as the target for each drying run. The impacts of ultrasonic-based pretreatments were investigated under a matrix of drying conditions (i.e., temperature (T), relative humidity (RH) & airflow (V)). Three levels of drying air temperature (60, 70 & 80°C) and two levels of drying air relative humidity (15 & 30%) were tested. All drying experiments were replicated twice.

Large scale drying experiments

A number of drying trials for the 2014 fruit harvest season were further carried out to demonstrate the scalability of the pretreatment and drying processes and the impact of such large scale experiments on the rehydrability and pitting of dried plums at industrial scale conditions, and the corresponding changes in microstructure and antioxidant activity levels. The large scale experiments were undertaken using about 2.6 kg of fresh plums per experimental treatment (~15 times larger than the small scale experiments). Two sets of large scale experiments (i.e., 3 replicates each set), including without pretreatment (control) and with pretreatment (i.e., using the combined ultrasound and oil emulsion) were carried out and the samples were then subsequently dried at 60°C until the final moisture content reached to the desired level (~20%). The dried samples were sent to Country Foods Pty Ltd (Young, NSW) for rehydration and pitting under commercial conditions.

Simulated industrial drying experiments

A number of laboratory drying experiments were conducted for the 2015 fruit harvest season to mimic the industrial tunnel drying of plums both in the counter-flow and parallel-flow modes of operation. In a simulated counter-flow drying, the drying air temperature was set initially at 55°C then increased linearly until up to 75°C for a total drying time of 30 hours and the corresponding drying air relative humidity was set initially at 35% then linearly decreased as drying progresses until the relative humidity reaches 15%. The selected temperature and relative humidity profiles are representative of the current commercial prune tunnel drying operations (Sabarez, 2010). In addition, under these counter-flow conditions the effects of ultrasound-based pretreatment at two levels of drying air velocity (1.0 & 2.5 m/s) and the time of harvest (fruit samples from early & late harvest) were studied. For the simulated parallel-flow drying, the drying temperature was set initially at 67°C then decreased linearly down to 55°C whilst the corresponding drying air relative humidity was set initially at 23% and progressively increased to 35%. The drying process under these simulated parallel-flow conditions was carried out for a total drying time of 18 hours.

Quality Analyses

Vitamin C and Antioxidant Capacity

Samples of the dried plums were sent to an external laboratory (National Measurement Institute or NMI, Port Melbourne, Victoria) for standard analyses of vitamin C and antioxidant capacity. The vitamin C (ascorbic acid) content of the filtrate was determined by normal phase HPLC on an Amino column using a phosphate buffer and acetonitrile mobile phase. Absorbance was measured by PDA detection at 245nm, the PDA spectra (220 to 350nm) was used as confirmation. Determination was made against known L-ascorbic acid and D-isoascorbic acid standards. Results are expressed to two significant figures in units of mg/100g. The antioxidant capacity was measured by Oxygen Radical Absorbance Capacity (ORAC) method. The ORAC assay provides a measure of antioxidant scavenging ability directed at the biologically prevalent peroxyl radical, a common reactive oxygen species (ROS). ORAC (hydro) represents the water-soluble antioxidant capacity and the ORAC (lipo) represents the fat-soluble antioxidant capacity of the sample. The water-soluble vitamin E analogue Trolox is used as the calibration standard and the ORAC (hydro) and ORAC (lipo) results are represented as μmol of Trolox equivalent per liter or kilogram. The total antioxidant capacity is the sum of ORAC (hydro) and ORAC (lipo) values and is also expressed as μmol of Trolox equivalent per liter or kilogram.

Microstructure

Plum samples (fresh & dried for 5 hours) were sent to the Electron Microscopy laboratory at CSIRO Materials Science and Engineering (Belmont, Victoria) for the microstructure analysis of the waxy skin layer of the samples using an Environmental Scanning Electron Microscopy (E-SEM) technique. In this technique, plums were skinned and the skin placed on adhesive carbon tape. For the images of the edge an injector blade was used to obtain a very sharp cut. All the imaging was done at a pressure of 50 Pa at room temperature using both backscattered and environmental secondary electron detectors. The detectors are noted on the images. BSE1 is the backscattered detector and ESED the secondary detector.

(a) (b) (c)

Figure 3. Photos of the (a) washing process, (b) steam oven, and (c) pitting machines in commercial operation at Country Foods Pty Ltd (Young, NSW).

Rehydration and Pitting

About 1 kg of each of the non-pretreated and pretreated dried plums obtained from large scale experiments were sent to Country Foods Pty Ltd (Young, NSW) for rehydration and pitting under commercial conditions. During rehydration, the dried plums were washed first with cold water (Figure 3a) prior to cooking with steam. The plums were then exposed for about 45 minutes inside the cooking oven (Figure 3b) heated with a steam of about 90°C temperature before conveyed to the pitting machines (Figure 3c) for the removal of stones. The acceptable pitted ones were then manually separated from the non-acceptable ones based solely on the company operators' discretion and experience and then weighed to determine the pitting efficiency.

Outputs

- Five milestone reports were submitted to update the industry with the progress of the project
- A progress report was submitted and published in the prune industry advisory committee HIA's 2013/14 annual report
- An article detailing the findings and progress of the project was published in an industry-based Journal (The Vine: The Bi-Monthly Journal for the Australian Table Grape and Dried Fruits Industries, Jan/Feb 2015)
- A presentation was delivered at the industry's annual conference in 2014 to provide a forum for discussion to assess the direction and activities of the project
- A final report
- Experimental prototypes of the ultrasonic-based pretreatment and drying systems

Outcome, Evaluation and Discussion

Proof of concept experimental investigations

A series of preliminary drying experiments were carried out to initially assess and screen the impact of a range of process variables at different levels on the rate of drying plums. Figure 4 shows a typical example of the results of the preliminary screening trials undertaken to initially evaluate the effects of pretreatment on the drying kinetics of plums. It can be seen from this plot that the combined application of ultrasound with oil emulsion had the highest effect in terms of accelerating the drying process under the conditions investigated. Fresh plums pretreated with ultrasound in oil emulsion were subsequently dried much faster compared to the non-pretreated fresh plums. The fresh plums pretreated with ultrasound in oil emulsion had their weight reduced by as much as 4 times compared with the non-pretreated samples after the 5-hour drying period. Using this screening approach, a suite of laboratory drying experiments were initially conducted to investigate and explore the effect of ultrasound pretreatment on the drying kinetics under different drying conditions and ultrasound parameters to establish the best process conditions.

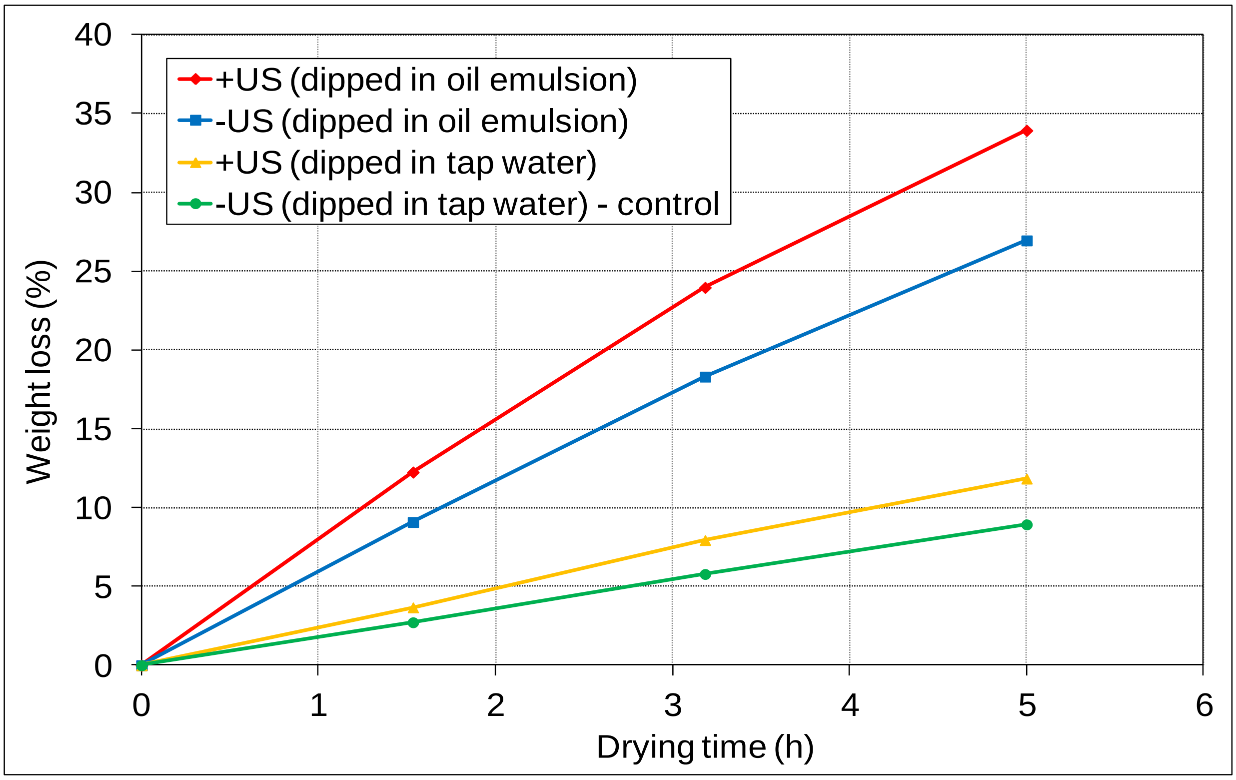


Figure 4. Typical example of the results of the preliminary screening trials (i.e. drying up to 5 hours) undertaken to initially assess the effects of different process variables on drying of plums (variety: GF 698) from 2013 harvest season. Pretreatment conditions (2% ethyl oleate in tap water emulsion; 25°C for 10 minutes), Ultrasound conditions (Power=460 W; Frequency=40 kHz), Drying conditions (T=60°C; RH=15%; V=2.5 m/s).

A number of laboratory drying experiments were further undertaken for the 2013 and 2014 fruit harvest seasons to investigate the effects of ultrasound pretreatments under various drying conditions on the drying performance (i.e., drying kinetics & total time). Each drying run for these trials was carried out until the desired final moisture of the dried fruit was reached (i.e., complete drying cycle). Figure 5 depicts the changes in moisture content during drying of the non-pretreated fruit and those pretreated at various pretreatment conditions. These experiments were undertaken employing the best ultrasonic pretreatment parameters and drying conditions established in the preliminary screening experiments. Under the conditions investigated, it is clear from the plot that the combination of ultrasound and oil emulsion pretreatment had the highest effect in terms of enhancing the drying process compared with ultrasound alone or oil emulsion alone pretreatments. It should be noted that fresh plums are often dried down to about 20% moisture content (wet basis) commercially. Analysis of the drying curves revealed that drying of plums without pretreatment (i.e., no ultrasound and just dipped in tap water as a control) took about 42 hours, 38 hours for fruit pretreated with ultrasound only in tap water, 23 hours for fruit pretreated with oil emulsion only, and just 19 hours for fruit pretreated with ultrasound in oil emulsion. In particular, the results showed that the combined ultrasonic pretreatment in oil emulsion significantly reduced the overall drying time of up to 55% in comparison with those samples dried without pretreatment to reach the desired final moisture content of the fruit. While the fresh fruit pretreated with ultrasound alone and oil emulsion alone reduced the total drying time by 10% and 45%, respectively.

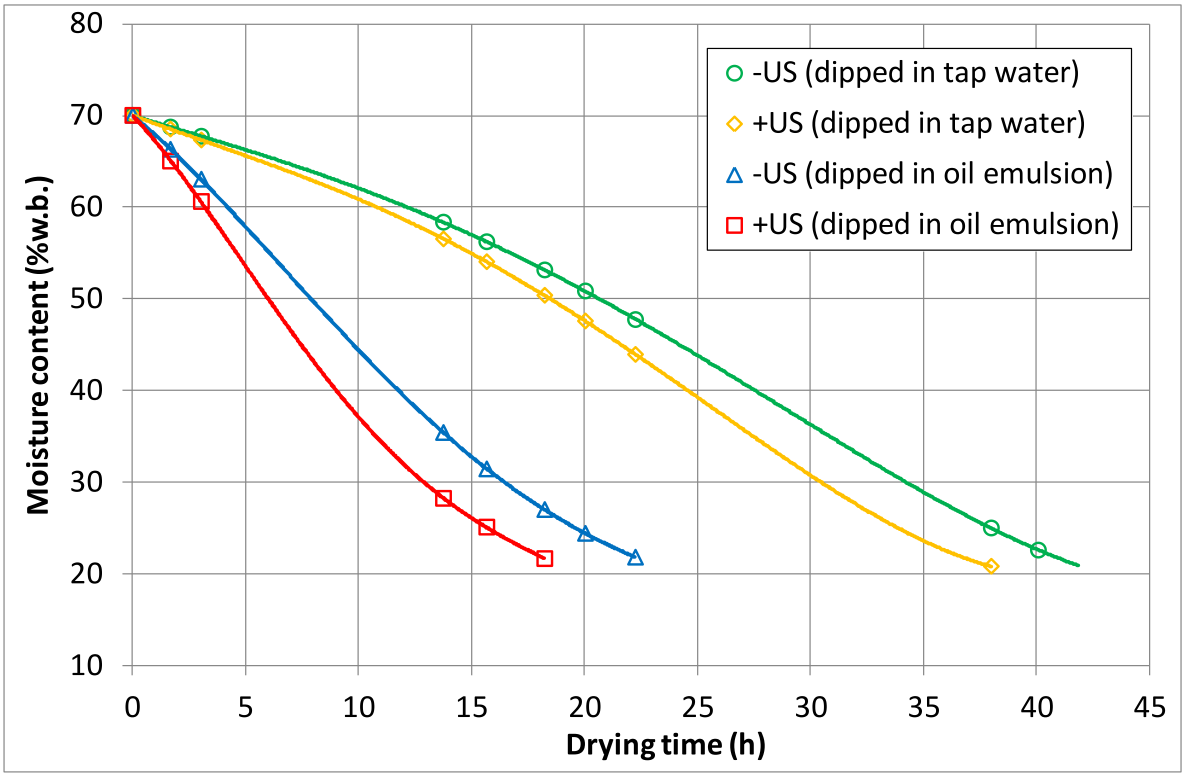


Figure 5. Effects of pretreatment combinations on the drying kinetics of plums (variety: GF698) obtained from 2013 fruit harvest season. Pretreatment conditions (2% ethyl oleate in tap water emulsion, 25°C for 10 minutes), Ultrasound conditions (Power=460 W; Frequency=40 kHz), Drying conditions (T=60°C; RH=15%; V=2.5 m/s).

It is interesting to note that the application of ultrasound pretreatment alone has only a marginal effect in terms of enhancing the drying process of plums (i.e., just about 10% or about 4 hours reduction in drying time under the conditions investigated). So far, no studies on the effect of ultrasound pretreatment specifically on drying of plums have been reported in the literature. However, a number of studies were reported on the impact of ultrasound pretreatment on the drying kinetics of other various food materials. For example, Fernandes and Rodrigues (2008) studied the influence of ultrasonic pretreatment prior to air drying on dehydration of sapota. These authors found that the ultrasonic pretreatment (frequency of 25 kHz; intensity of 4870 W/m^2; 25°C) for 10 min and 30 min reduced the drying by 19% and 23%, respectively. Also, Fernandes et al., (2008a) reported a 16% reduction in drying time with the application of ultrasonic pretreatment (frequency of 25 kHz; intensity of 4870 W/m^2; 25°C) for 20 min during air drying of papayas. Nowacka et al., (2012) showed that the ultrasound pretreatment (frequency of 35 kHz; 25°C) for 10 min caused a reduction of the drying time by 31% in comparison to non-pretreated samples during drying of apple cubes. Similarly, Fernandes et al., (2008b), who dried ultrasound pretreated pineapple reported a reduction of the drying time over 30% in comparison with the reference sample. Similar effects were described by Rodrigues and Fernandes (2007) for melon, Jambrak et al., (2007) for Brussels sprouts and cauliflower, García-Pérez et al., (2009) for lemon peel, Ortuño et al., (2010) for orange peel.

It can be observed from these previous studies that the influence of ultrasound pretreatment in enhancing the drying process varies for various types of raw materials. The raw materials used in the studies reported in the literature were cut into pieces (e.g., slices, cubes, halves), exposing the tissue of the raw materials directly to the pretreatment. On the other hand, fresh plums are normally dried as a whole fruit with the skin intact. It was postulated that the ultrasonic pretreatment affects the fruit tissue, making it easier for water to diffuse during the subsequent air drying, probably due to the formation of microscopic channels in the fruit tissue. The formation of micro-channels could be due the mechanical forces of the ultrasonic waves which cause a rapid series of alternate compression and expansion, in a way similar to a sponge when it is squeezed and released repeatedly Gallego-Juarez et al., (2007). This alternating acoustic stress subsequently creates microscopic channels that make internal water movement easier (Carcel et al., 2007). This is corroborated in a study by Fernandes et al., (2008b) who showed micrographs of the microscopic channels in melon tissue after the application of ultrasound. In the present study, the observed marginal effect of ultrasound pretreatment on plums could be due to the large resistance of the fruit to the mechanical action brought about by the ultrasonic waves for the creation of micro-channels as the fruit were pretreated as a whole with skin intact. It was therefore thought that the observed effect of ultrasonic pretreatment in enhancing the drying process of plums could be mainly due to other mechanisms brought about by the application of ultrasound. It is known for many years that the energy generated by sound pressure waves could enhance a wide range of processes due to a series of mechanisms activated by the ultrasonic energy such as heat, diffusion, mechanical rupture, chemical effects, etc (Gallego-Juarez et al., 2007).

In liquids, when ultrasonic power attains a threshold, the rarefaction cycle may exceed the attractive forces and, from existing gas nuclei, cavitation bubbles could appear (Soria and Villamiel, 2010). These bubbles could maintain a stable increasing and decreasing size giving rise to the so-called "stable cavitation" generating a micro-agitation of the medium. However, the bubbles can also grow and collapse, generating very high local temperatures (5000 K) and pressures (1000 atm), which produce, in turn, high energy shear waves and turbulence in the cavitation zone. This last effect is known as "transient cavitation" (Leighton, 1998). The implosions are asymmetric if produced near a solid surface generating a microjet that hits the solid (Mason, 1998) (Figure 6). This is the main effect observed in the use of high intensity ultrasound (high power & low frequency) in cleaning operations. This is thought to be the main mechanism responsible for the enhancement in the drying process of plums by disrupting their waxy skin layer during the ultrasonic pretreatment to improve fruit skin's water permeability. However, the ability of ultrasound to cause cavitation depends on ultrasound characteristics (e.g., frequency, intensity), product properties (e.g., viscosity, surface tension) and ambient conditions (e.g., temperature, pressure). It should be noted that the waxy skin layer of plums has been demonstrated in previous studies to provide a significant barrier to moisture transfer during the drying process depending on the drying temperature (Price et al., 2000; Sabarez, 1998).

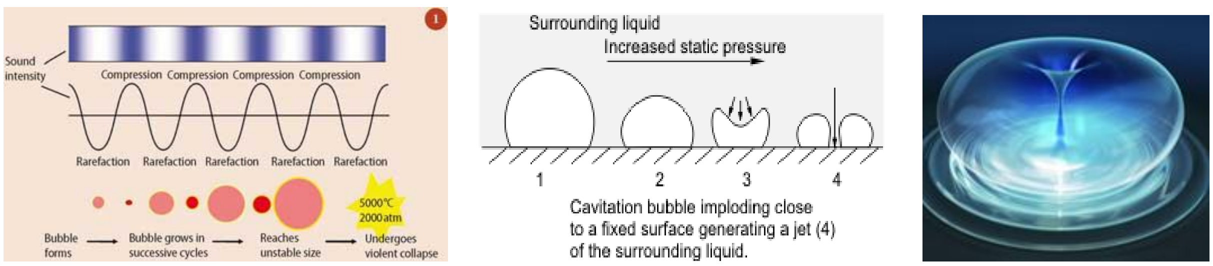


Figure 6. Cavitation generation and implosion mechanisms during ultrasound application in liquid.

Another interesting feature that can be gleaned from the results depicted in Figure 5 is the significant effect in enhancing the drying process of plums pretreated with oil emulsion only. It can be seen in the figure that a 45% reduction in drying time can be achieved with the oil emulsion pretreatment only in comparison to the non-pretreated samples (control) under the drying conditions investigated. The skin layer of fresh plums is known to consist of a cuticle coated with hydrophobic waxes, which represents an efficient barrier to water movement particularly during drying at low temperatures (Figure 7). Price et al., (2000) have observed a significant disruption of the structure of the waxy skin layer by SEM technique of plums dried at 70°C and above, which significantly increases the permeability of the skin layer to moisture transfer during drying. Thus, the resistance offered by the waxy skin layer to moisture transfer can be minimised by utilising higher drying temperatures. However, for most foodstuffs caution is required because higher temperatures may alter their physical and chemical constituents, which affect the quality of the dried product. Hence, the use of higher drying temperatures is limited to a point below which the undesirable characteristics are minimised. In plum drying, the maximum allowable temperature was reported to be up to 85°C (depending on fruit maturity, humidity, airflow, mode of tunnel operation, etc.), as drying above this temperature would result in excessive bleeding and splitting of the fruit and possibly caramelisation and off flavour production (Sabarez et al., 2000; Gentry et al., 1965). Also, increases in temperature would generally mean an increase in energy input requirement.

To overcome the limitations of utilising elevated temperatures, previous studies on grapes (Uhlig, 1993; Ponting and McBean, 1970) were undertaken to examine the effect of dipping oil emulsion pretreatments designed to modify or remove the waxy skin layer to speed up the drying process at lower temperatures of fruits having a waxy skin layer. This approach is a chemical operation intended to disrupt the waxy skin layer of the fruit thereby altering its water permeability. The method of pretreatment evolved from the Greek procedure of dipping grapes in emulsions of olive oil and potash (wood ash) in water before drying. In modern times, olive oil was replaced by specially formulated dipping oil, mainly ethyl esters of fatty acids (with ethyl oleate as the most effective compound) and the wood ash was replaced with a food-grade potassium carbonate (K_2CO_3). The application of dipping emulsions has been extensively studied (Uhlig, 1993; Ponting and McBean, 1970) to accelerate the drying of grapes and currently used commercially in sultana production in Australia. A promising result from the early work by Ponting and McBean (1970) on the use of alkaline ethyl oleate as dipping treatment prior to drying of plums has provided the basis for a further study conducted by Sabarez (1998), who reported a 20% reduction in drying time (about 4 hours) of plums pretreated with drying emulsion (2.5% K_2CO_3 + 2% ethyl oleate) with the subsequent drying process carried out at 70°C temperature. Also, Doymaz (2004) reported a 29.4% reduction in drying time for plums pretreated with dipping emulsion containing 5% K_2CO_3 and 2% ethyl oleate in comparison to the untreated samples with the drying process carried out at 65°C temperature.

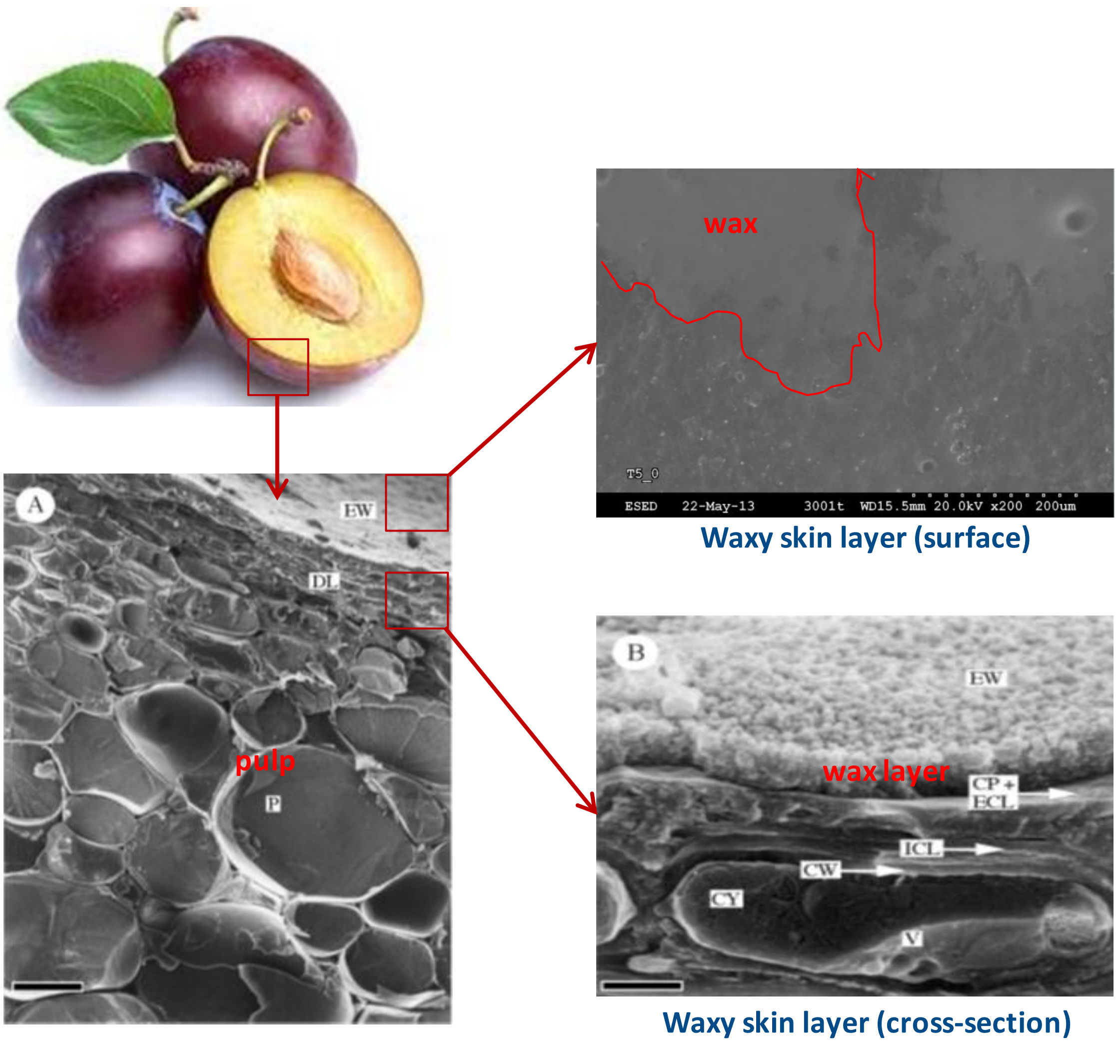
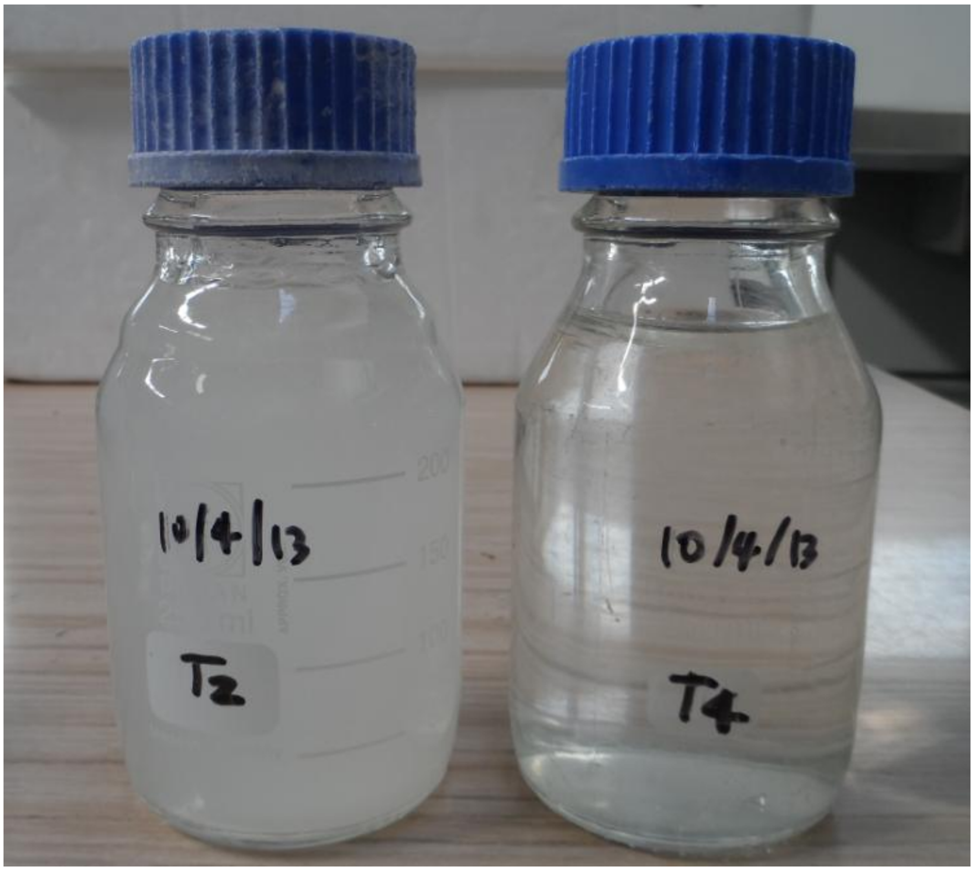


Figure 7. Microstructure of the waxy skin layer of fresh plums.

Based on these earlier studies on plums, it was therefore thought worthwhile investigating further the use of oil emulsion to enhance the drying process of plums, particularly at lower drying temperatures.

The oil component (i.e., ethyl oleate) in the drying emulsion is considered as the most important constituent in enhancing the drying process. Other components (potassium carbonate or emulsifiers) are mainly added to form a stable emulsion at ambient conditions with little or no additive effect of enhancing the drying process (Ponting and McBean, 1970). In some cases, the addition of potassium carbonate was reported to influence the conversion of the wax from hydrophobic to hydrophilic condition and would probably facilitate the penetration of esters into the cuticle. However, according to Barnet (1980), the important role of potassium carbonate is mainly to contribute to increase the pH of the solution, which assists in maintaining a stable emulsion of oil in water.



(a) (b)

Figure 8. Photos of the oil emulsions (2% ethyl oleate in tap water) used in the pretreatment and taken after 5 months of storage without further mixing (a) pretreated with ultrasound at 40 kHz, 460 W for 10 min and (b) non-pretreated.

In the present study, ethyl oleate was used as the main oil component while the use of potassium carbonate or other emulsifiers for its main role in forming a stable emulsion of oil in water was replaced with the use of ultrasound (i.e., to eliminate further use of chemicals). High power ultrasound (i.e., low frequency) has been shown to effectively emulsify oil in water solution (Abismail et al., 1999; Cucheval and Chow, 2008). Figure 8 shows the stability of oil emulsion treated with and without ultrasound. It can be seen in the figure that the oil emulsion subjected with ultrasound has maintained stability after 5 months of storage. Aside from this emulsifying effect, the pretreatment of plums in oil emulsion with the application of ultrasound was hypothesized to provide synergistic effects in modifying the fruit waxy skin layer by physically disrupting the outer waxy layer in the skin surface of the fruit through the mechanism described above and facilitating the oil penetration into the cuticle to interact with the waxes and establish a hydrophilic link (i.e., water-conducting channel). This is demonstrated in the disruption of the waxy surface layer brought about by the combined ultrasound and oil emulsion pretreatment as depicted in Figure 9. It can be clearly seen in the SEM micrographs that the surface waxes in plums pretreated with the combined ultrasound and oil emulsion were significantly disrupted and thoroughly disorganised while in the non-pretreated plums the surface waxes were still intact. This results a further 11% reduction in drying time (about 4.5 hours) with the combined ultrasound and oil emulsion pretreatment in comparison with the oil emulsion alone pretreatment (Figure 5).

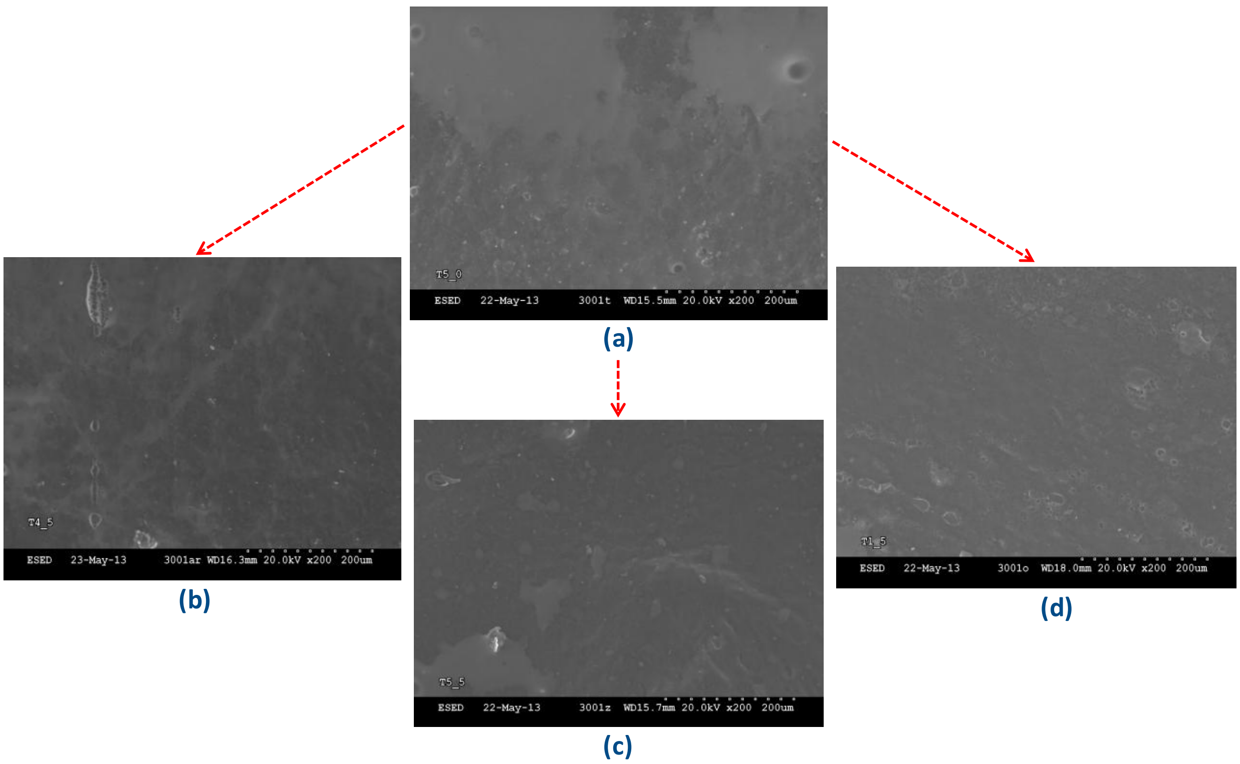


Figure 9. E-SEM micrographs of the skin surface layer of (a) fresh plum, and the plums dried after 5 hours (b) pretreated with ultrasound only, (c) non-pretreated, and (d) pretreated with ultrasound in oil emulsion. Pretreatment conditions (2% ethyl oleate in tap water emulsion, 25°C for 10 minutes), Ultrasound conditions (Power=460 W; Frequency=40 kHz), Drying conditions (T=60°C; RH=15%; V=2.5 m/s).

It was also observed that the magnitude of the effect of the combined ultrasound and oil emulsion pretreatment in enhancing the drying process of plums is dependent on other process parameters. Figure 10 shows the drying kinetics of plums pretreated with the combined ultrasound and oil emulsion, oil emulsion alone and without pretreatment (control). The fresh plums used in these experiments were from a different orchard with different initial moisture content and fruit variety. It can be seen in this figure that a 17% (about 8 hours) reduction in drying time was found with the combined ultrasound and oil emulsion pretreatment in comparison with the oil emulsion only pretreatment. In addition, the effect of the combined ultrasound and oil emulsion in comparison with the non-pretreated (control) was also consistent with the previous experiments shown in Figure 5 (i.e., different orchard & fruit variety), resulting in a 57% (about 27 hours) reduction in drying time.

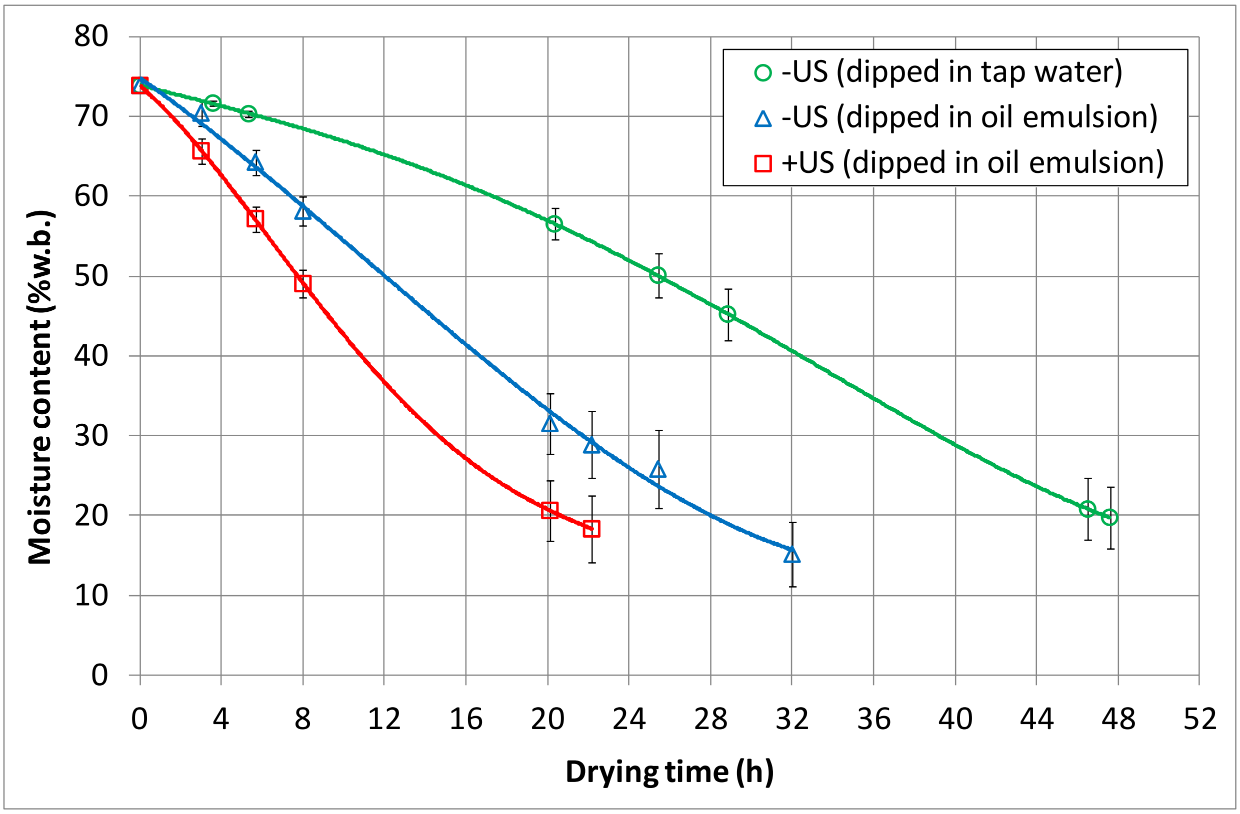


Figure 10. Effects of ultrasound oil emulsion pretreatment on the drying kinetics of plums (variety: 303) obtained from 2013 fruit harvest season. Pretreatment conditions (2% ethyl oleate in tap water emulsion, 25°C for 10 minutes), Ultrasound conditions (Power=460 W; Frequency=40 kHz), Drying conditions (T=60°C; RH=15%; V=2.5 m/s).

Effect of pretreatment parameters on drying kinetics

The impacts of pretreatment parameters, including sonication time, ultrasonic frequency and emulsion recycling on the drying process were further investigated. Three levels of pretreatment sonication time (1, 5 and 10 min) were studied using the best pretreatment conditions (i.e., combined ultrasound & oil emulsion, ultrasonic frequency) initially established in the previous experiments. The pretreated samples were then subsequently dried at 60°C. No significant differences in the drying time between samples pretreated for 1 min and 5 min were observed (Figure 11). The figure also shows that the samples pretreated for 10 min showed a slightly shorter drying time compared with the samples pretreated with the other two sonication times. It was observed visually that a further increase in sonication time (above

10 minutes) resulted in splitting of the fruit skin. This finding suggests that a shorter pretreatment time could be employed while still achieving an effective pretreatment. A shorter pretreatment time is ideal as it usually requires a large throughput capacity at industrial scale operation for the technology to be commercially viable. On the other hand, there was only a marginal effect of ultrasonic frequencies tested (40 kHz & 270 kHz) in terms of reducing the drying time, with plums pretreated at 40 kHz were dried slightly faster than those plums pretreated at 270 kHz. No significant differences in drying time were found for re-using the emulsion solution pretreatment for at least 3 times. This could provide a further cost saving avenue with the use of oil emulsion pretreatment. It should be kept in mind that the active oil component (i.e., ethyl oleate) of the emulsion used in these experiments was already at a minimal amount (2% v/w).

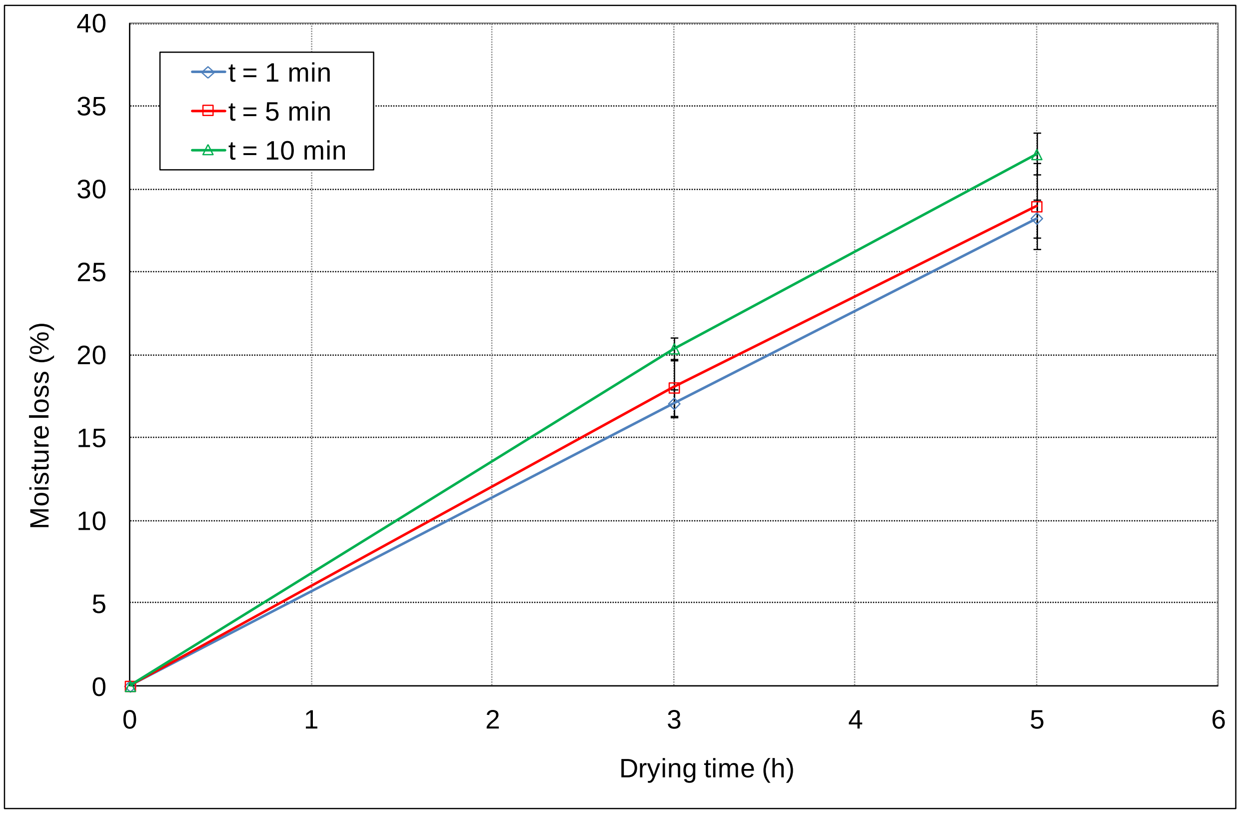


Figure 11. Weight loss during drying of plums (variety: GF698; 2014 fruit harvest season) pretreated at different pretreatment times with ultrasound in oil emulsion. Pretreatment conditions (2% ethyl oleate in tap water emulsion, 25°C), Ultrasound conditions (Power=460 W; Frequency=40 kHz), Drying conditions (T=60°C; RH=15%; V=2.5 m/s).

Further experiments were carried out to investigate the effect of vegetable oils (e.g., olive oil & coconut oil) as potential alternative to ethyl oleate as the main active constituent in the dipping emulsion to further reduce the pretreatment costs while still maintaining its effectiveness in enhancing the drying process. The use of these oils is potentially a cost-effective approach because they are relatively inexpensive (~$3/liter for canola oil) and plentiful as compared to ethyl oleate (~$100/liter). In particular, the relatively high proportion of oleic acid in olive oil may provide similar impacts with ethyl oleate in terms of enhancing the drying process. Unsaturated fatty acids, including oleic acid ethyl ester are most effective, probably because of their molecular structure and bonding, which enable them to penetrate into the cuticle and alter the arrangement of the wax components (Christensen and Peacock, 2000). Figure 12 shows the effects of other two oils tested as the main component in the ultrasound oil emulsion pretreatment on drying kinetics of plums. The results indicate the potential of these two oils as an alternative main constituent in the drying emulsion. These oils have provided significant effect in enhancing the drying process, although not as effective as ethyl oleate. It is therefore important to further optimise the use of these oils as an alternative to ethyl oleate, especially in large scale trials and by undertaking a cost-benefit analysis on the use of such oil.

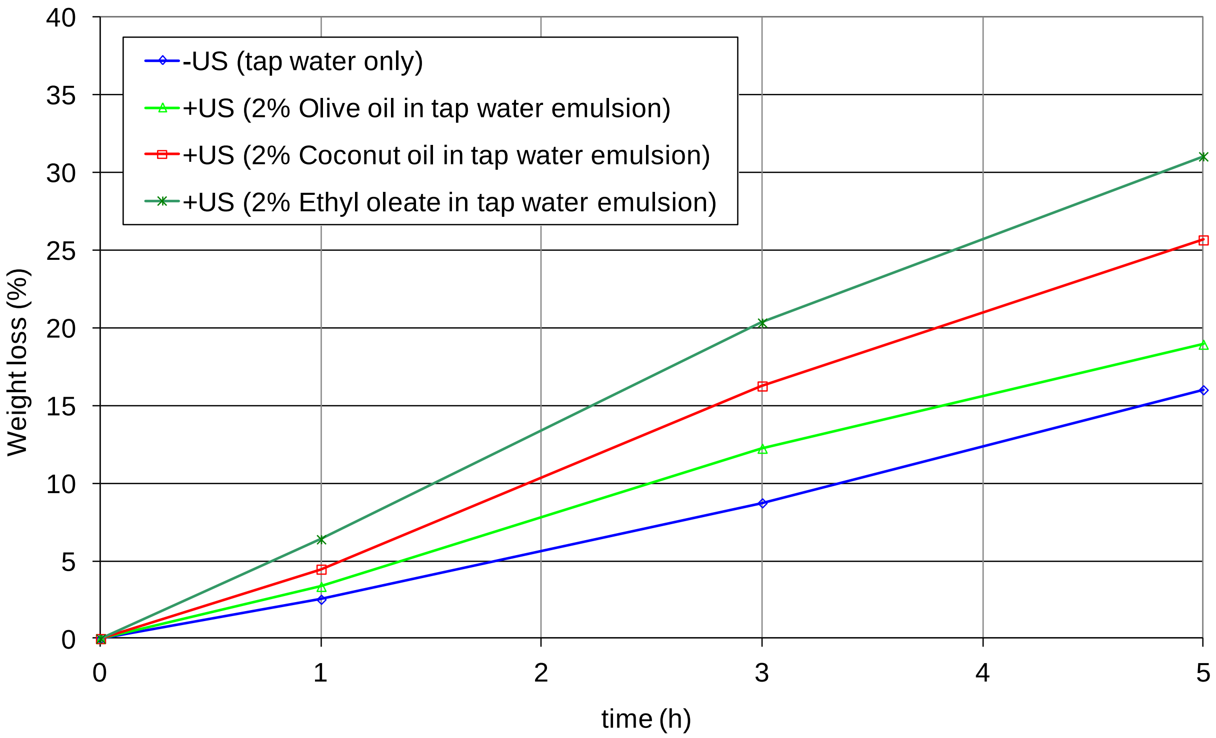


Figure 12. Weight loss during drying of plums (variety: GF698; 2013 fruit harvest season) pretreated with ultrasound in oil emulsion with different types of oil. Pretreatment conditions (25°C for 2 min), Ultrasound conditions (Power=460 W; Frequency=40 kHz), Drying conditions (T=60°C; RH=15%; V=2.5 m/s).

Effect of pretreatment on quality attributes

The utilisation of higher temperatures to accelerate the drying process or the use of lower temperatures (at the expense of longer drying times) could possibly result in inferior quality of the dried products. In the present study, the effects of the combined ultrasound and oil emulsion pretreatment on the quality attributes of the dried plums were compared with those plums dried without pretreatment. The subsequent drying experiments for the non-pretreated plums were carried out at two levels of drying air temperature (80 & 60°C) to simulate the extreme high and low temperature drying conditions typical in industrial drying operations. On the other hand, the pretreated plums were subsequently dried at low temperature (60°C). The drying process was carried out until the final moisture content of the fruit reached around 20% moisture content. The quality attributes of the dried product that were investigated include antioxidant capacity, vitamin C and colour. Results of these experiments are presented in Table 1.

Table 1. Effect of ultrasound oil emulsion pretreatment on product quality attributes. Pretreatment conditions (2% ethyl oleate in tap water emulsion; 25°C for 10 min), Ultrasound conditions (Power=460 W; Frequency=40 kHz), Drying conditions (RH=15%; V=2.5 m/s).

Treatment	Quality attributes			
	Colour	Moisture Content (% wet basis)	Vitamin C (mg/100g dry weight)	Antioxidant (T.E. µmol/100g dry weight)
Fresh plums		70.03	3.34	2502.5
Non-pretreated plums dried at 80°C		20.37	<0.13	5098.6
Non-pretreated plums dried at 60°C		22.57	<0.13	4210.2
Pretreated plums dried at 60°C		21.64	0.23	5832.1

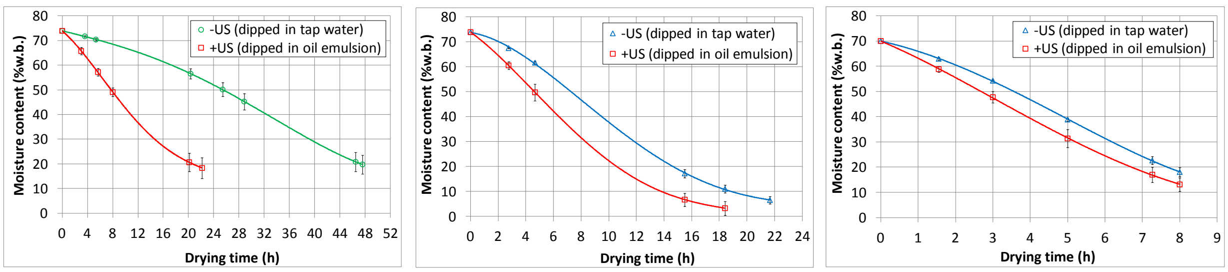
For the non-pretreated plums dried at 80°C and 60°C, the drying process took about 9 hours and 40 hours, respectively, to dry down to the desired final moisture content level. On the other hand, it took just about 18 hours to dry pretreated plums at low temperature (60°C), a reduction in the drying time of about 22 hours for pretreated plums compared with those without pretreatment dried at the same low temperature (60°C). It can be seen in Table 1 that the non-pretreated samples dried at high temperature/short drying time and low temperature/long drying time both resulted in very low levels of vitamin C. On the other hand, drying of non-pretreated plums at high temperature/short drying time resulted in a better retention of the antioxidant capacity compared with those non-pretreated plums dried at low temperature/long drying time. However, the plums pretreated with the combined ultrasound and oil emulsion had superior quality attributes amongst of the studied parameters. It was found that the retention of both the antioxidant capacity and vitamin C was significantly higher with lighter colour for the dried samples ultrasonically pretreated in oil emulsion compared with the non-pretreated samples. This is consistent with the fact that the pretreated plums were dried at low temperature and short drying time compared to the non-pretreated plums, which were dried either at high temperature or long drying time. It is also interesting to observe that the drying process resulted in a significant reduction in vitamin C, regardless of the pretreatment and drying conditions, suggesting the heat sensitivity of vitamin C to thermal treatment. The antioxidant capacity of dried plums pretreated with ultrasound in oil emulsion was about 28% higher compared with the non-pretreated dried plums. The result is also notable due to the fact that the antioxidant capacity levels of the dried plums were significantly higher (up to 57%) compared with the fresh plum samples. It should be emphasised that the amounts of vitamin C and antioxidant capacity presented in Table 1 were calculated based on the dry matter content of the product to correct the effect of the amount of water in the product. The result suggests that the drying process may enhance the bio-availability of the health-promoting components in the fruit with the magnitude of influence depends on the pretreatment and drying conditions.

Effect of pretreatment at various drying conditions on drying kinetics

In convective drying of food materials (like plums), the conditions of the drying air are considered to be the main factors influencing the drying performance. In particular, it is recognised that the coupled heat and mass transport phenomena simultaneously occurring during convective drying of food materials are usually influenced by these parameters. Therefore, a better knowledge of the influence of any pretreatments on the drying process at different drying conditions could facilitate an improved understanding of the mechanism in which pretreatment enhances the convective drying of plums. In the present study, the effects of the best pretreatment conditions (i.e., established in previous experiments) on the drying process of plums under different drying air temperature and relative humidity levels were investigated. It should be noted that an investigation on the effects of pretreatment at various levels of drying conditions is important in order to apply the results to large scale operations, as the drying conditions (i.e., particularly temperature and relative humidity) in industrial tunnel dryers are systematically changing with drying time and position in the drying tunnel.

The influence of the combined ultrasound and oil emulsion pretreatment in intensifying the drying process at three levels of drying air temperature (60, 70 & 80°C) was studied. The selected drying temperatures are typical conditions that can be found in industrial tunnel drying of plums (Sabarez, 2010). In these experiments, all other drying conditions (i.e., relative humidity & airflow) were kept constant throughout each the drying run. Figure 13 depicts the changes in moisture content of the non-pretreated (control) and pretreated fruit during drying at various drying temperatures. Plums are often dried down to 20% moisture content (commercially). Analysis of the plots show that the non-pretreated and pretreated plums took about 42 hours and 20 hours, respectively to dry at 60°C temperature, while it took about 14.5 hours (non-pretreated) and 10.5 hours (pretreated) to dry at 70°C temperature, and just 7.5 hours (non-pretreated) and 6.5 hours (pretreated) at 80°C temperature.

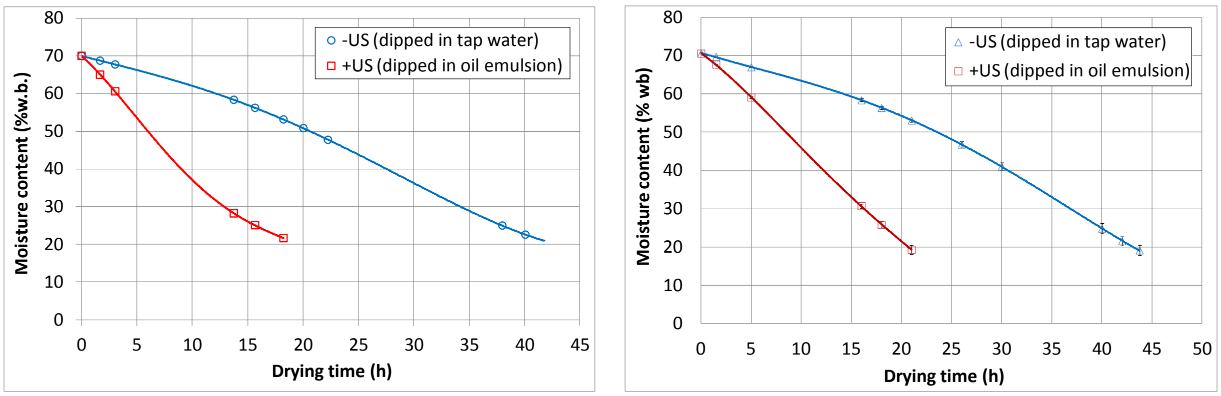
The results from these experiments reveal that the effect of pretreatment varies significantly with the different drying temperatures. In particular, the ability of the combined ultrasonic and oil emulsion pretreatment to improve the efficiency in the drying process appears to be maximised when using lower drying temperature and that the effect of pretreatment progressively decreases as the drying temperature increases. For example, drying at 60°C resulted in 52% (about 22 hours) reduction in the overall drying time with the application of pretreatment while drying at 70°C and 80°C with the pretreated samples resulted in 28% (about 4 hours) and 13% (about 1 hour) reduction in the overall drying time, respectively. The result is notable in that there appears to be a substantial enhancement in the drying process as affected by pretreatment during drying at temperatures below 70°C. This could be attributed to the efficiency of cell disruption induced by drying, particularly in the waxy skin layer of the fruit as demonstrated in previous studies. Price et al., (2000) have observed significant disruption of the structure of the waxy skin layer by SEM technique of plums dried at 70°C and above, which significantly increases the permeability of the skin layer to moisture transfer during drying. Unpublished data of Johnson and McBean as cited by Bain and McBean (1967) suggested that the lowest melting point of any component of plum wax is 56°C, while the wax as a whole does not melt until about 65°C. Also, Bain and McBean (1967) found that the normal surface structure of the waxy layer in plums showed some alterations at 54°C, but was not completely disorganised until 66°C. Therefore, the application of pretreatment in enhancing the subsequent drying process by disrupting the waxy skin layer to increase its permeability to moisture transfer during drying would not be as effective at higher temperatures studied (above 70°C) since under these conditions the resistance to moisture transfer in the waxy skin layer was already substantially reduced by the thermal treatment alone. This indicates that with the application of pretreatment, drying of plums can be carried out at lower drying temperature while still achieving faster drying rates (i.e., resulting in increased throughput and reduced energy consumption).



(a) T = 60°C (b) T = 70°C (c) T = 80°C

Figure 13. Effects of different drying air temperatures on the drying kinetics of plums (variety: 303; 2013 fruit harvest season) pretreated with ultrasound in oil emulsion. Pretreatment conditions (2% ethyl oleate in tap water emulsion, 25°C for 10 min), Ultrasound conditions (Power=460 W; Frequency=40 kHz), Drying conditions (RH=15%; V=2.5 m/s).

The relative humidity of the drying air is another important parameter that significantly affects the drying process of plums (Sabarez, 2010). A number of of experiments were undertaken to examine the effect of ultrasound in oil emulsion pretreatment at two different levels of drying air relative humidity (15% & 30%), which can typically be found in industrial tunnel drying conditions. All other drying conditions (i.e. temperature & airflow) were also kept constant throughout each drying experiment. Figure 14 shows the changes in moisture content of the non-pretreated (control) and pretreated fruit during drying at two levels of relative humidity. Analysis of the drying curves reveals that drying of the non-pretreated and pretreated plums at 30% relative humidity took about 43.5 hours and 20.5 hours, respectively, while it took about 42 hours (non-pretreated) and 20 hours (pretreated) to dry plums at 15% relative humidity. Drying at 30% relative humidity resulted in 52.9% (about 23 hours) reduction in the overall drying time with the application of pretreatment while drying at 15% relative humidity with the pretreated samples resulted in 52.4% (about 22 hours) reduction in the overall drying time. The results from these drying trials indicate that the effect of pretreatment is slightly better at higher drying relative humidity condition, under the range of conditions investigated. It should be noted that the amount of moisture in the air is recognised to affect the kinetics of moisture removal during convective drying of food materials. However, according to Heldman and Hartel (1997), the main influence of relative humidity is limited to the drying period in which the external rate of moisture evaporation from the food surface to the drying air governs the drying process (i.e., constant rate period) and has little impact during the drying period which is controlled by the rate of internal moisture movement within the food matrix (i.e., falling rate period). This means that the drying process of plums under the range of relative humidity conditions investigated is mainly limited by the rate of internal moisture transfer across the waxy skin layer, suggesting that the pretreatment could be as effective at industrial scale drying operations as the relative humidity of the drying air in industrial drying of plums changes dynamically with time and position in the drying tunnel according to this range (Sabarez, 2010).



(a) RH = 15% (b) RH = 30%

Figure 14. Effects of different levels of drying air relative humidity on the drying kinetics of plums (variety: GF698; 2013 fruit harvest season) pretreated with ultrasound in oil emulsion. Pretreatment conditions (2% ethyl oleate in tap water emulsion, 25°C for 10 min), Ultrasound conditions (Power=460 W; Frequency=40 kHz), Drying conditions (T=60°C; V=2.5 m/s).

Scale-up experiments

A number of laboratory drying trials for the 2014 fruit harvest season were further carried out to demonstrate the scalability of the pretreatment and drying process and the effect of such large scale experiments on product quality attributes. Figure 15 shows the drying kinetics of the non-pretreated and pretreated plums for the large scale experiments. Analysis of the drying curves unveils that drying of non-pretreated plums took about 42 hours while it took just about 17 hours to dry the pretreated plums under the same drying conditions. This corresponds to a 60% (about 25 hours) reduction in the overall drying time under the conditions studied with the application of pretreatment. The result is consistent with those obtained in the small scale experiments, demonstrating the scalability of the pretreatment and drying process.

Table 2 presents the impact of pretreatment in large scale experiments on the quality attributes of the dried product. In particular, the effect on pitting efficiency is one of the most important quality attributes of major concern to the industry. Dried plums are usually rehydrated to obtain the final product that is ready for consumption. Some of these rehydrated products are sold in the market with stones removed (i.e., pitted). The possibility of the integration of plums during the rehydration and pitting process was examined as any pretreatments designed to disrupt the skin layer of the fruit could potentially result in poor integrity of this skin layer (i.e., cracking/splitting of the skin and loss of juice). For example, it was found in previous studies that pretreatment of plums with alkaline caustic soda resulted in poor integrity of the fruit on rehydration (Sabarez, 1998). Pitting efficiency is an industry standard measure of the integrity of the fruit on rehydration and pitting. It can be seen in the table that no significant differences in the pitting efficiency between the non-pretreated and the pretreated samples were observed. The values of pitting efficiency obtained in these large scale experiments were consistent with those obtained commercially (personal communication, Country Foods P/L). This suggests that there would be no problem of incorporating the pretreatment process into the current industrial scale operation. In addition, the pretreated samples were found to have a lighter colour with higher antioxidant capacity level (about 33% more) compared with the non-pretreated samples as shown in Table 2, corroborating the results from the small scale experiments. The observed better quality product is consistent with the fact that the pretreated plums were subsequently dried at low temperature and short drying time. The disruption of the waxy skin layer with the application of pretreatment is consistent with the observed significant reduction in drying time as a consequence of improved moisture transfer across the waxy skin layer of the fruit as demonstrated in the SEM micrographs in the table showing a thoroughly disorganised wax layer.

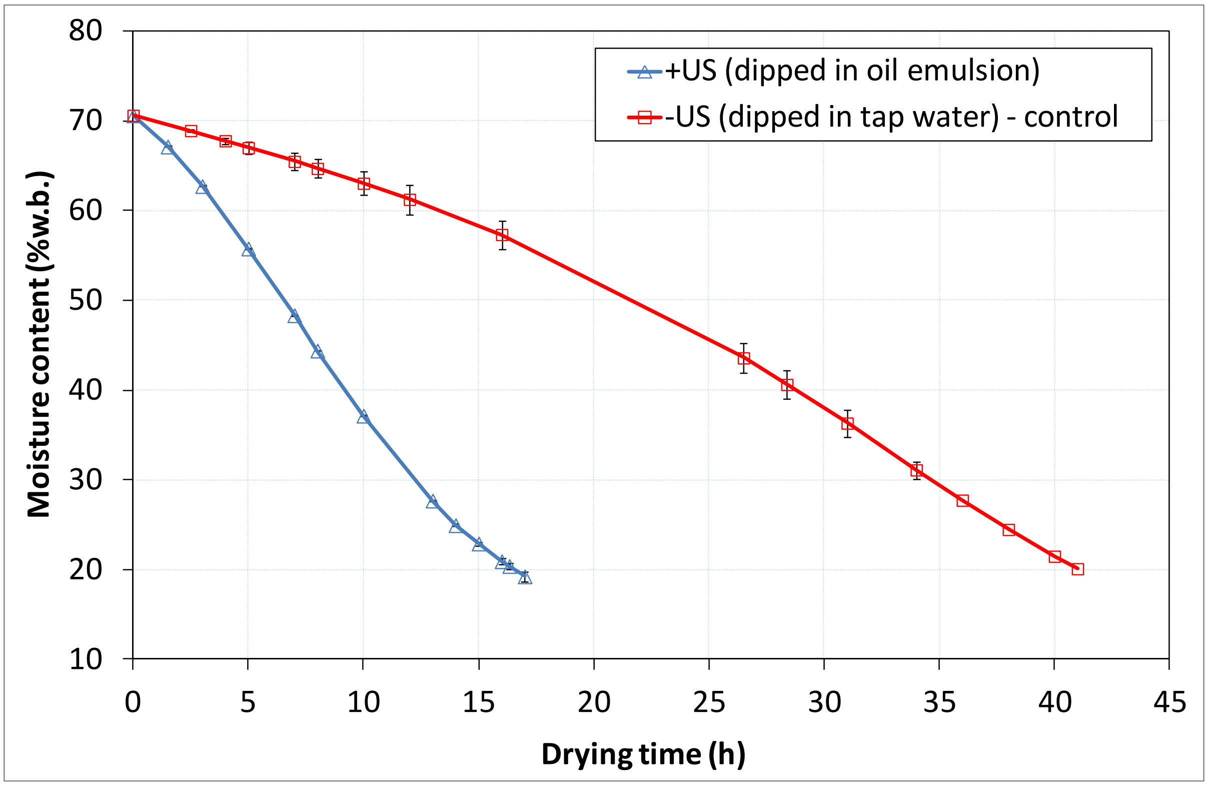


Figure 15. Drying kinetics of plums (variety: GF698; 2014 fruit harvest season) non-pretreated and pretreated with ultrasound in oil emulsion in large scale experiment. Pretreatment conditions (2% ethyl oleate in tap water emulsion, 25°C for 10 min), Ultrasound conditions (Power=520 W; Frequency=40 kHz), Drying conditions (T=60°C; RH=15%; V=2.5 m/s).

Table 2. Effect of large scale ultrasound oil emulsion pretreatment on product quality attributes. Pretreatment conditions (2% ethyl oleate in tap water emulsion; 25°C for 10 min), Ultrasound conditions (Power=520 W; Frequency=40 kHz), Drying conditions (T=60°C; RH=15%; V=2.5 m/s).

Treatment	Quality attributes			
	Colour	Moisture Content (% wet basis)	Pitting Efficiency (%)	Antioxidant (T.E. μmol/100g dry weight)
Fresh plums		70.3	-	4494.9
Non-pretreated		36.5	82.31	6946.5
Pretreated		36.2	82.14	10388.7

Note: The non-pretreated and pretreated plums were first dried down to 20% moisture & then rehydrated to the moisture content shown in this table.

Simulated industrial drying experiments

The main focus of these experiments was to investigate the effect of the best pretreatment conditions (i.e., combined ultrasound and oil emulsion as established in previous experiments) on the drying process under simulated conditions typical in industrial scale tunnel drying system. It should be noted that the drying conditions (i.e., particularly temperature and relative humidity) at industrial tunnel dryers are systematically changing with drying time and position in the drying tunnel, depending on the mode of operation. The industrial tunnel dehydrators are currently operated in either counter-flow or parallel-flow mode of operation (Figure 16).

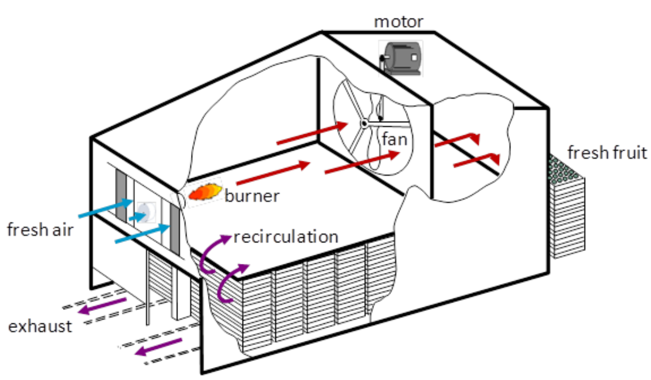


Figure 16. Schematic diagram of a typical tunnel dehydrator used in commercial drying of plums (Sabarez, 2015; Sabarez, 2010).

In a counter-flow configuration, the drying air is introduced into one end of the tunnel while the trolleys of fresh fruits enter at the other end and each moves in opposite directions. This configuration is characterised by having conditions most conducive to intense heating at the end of the drying cycle when the products are nearly dry and mild heating in the early stages. The operation of the parallel-flow tunnel is opposite to that of the counter-flow. The trolleys of fresh fruits and drying air enter at the same end of the tunnel and progress through the tunnel in the same direction. This configuration is characterised by intense heating in the early stages where the products to be dried are still very wet followed by slow drying as the product approaches the cooler end.

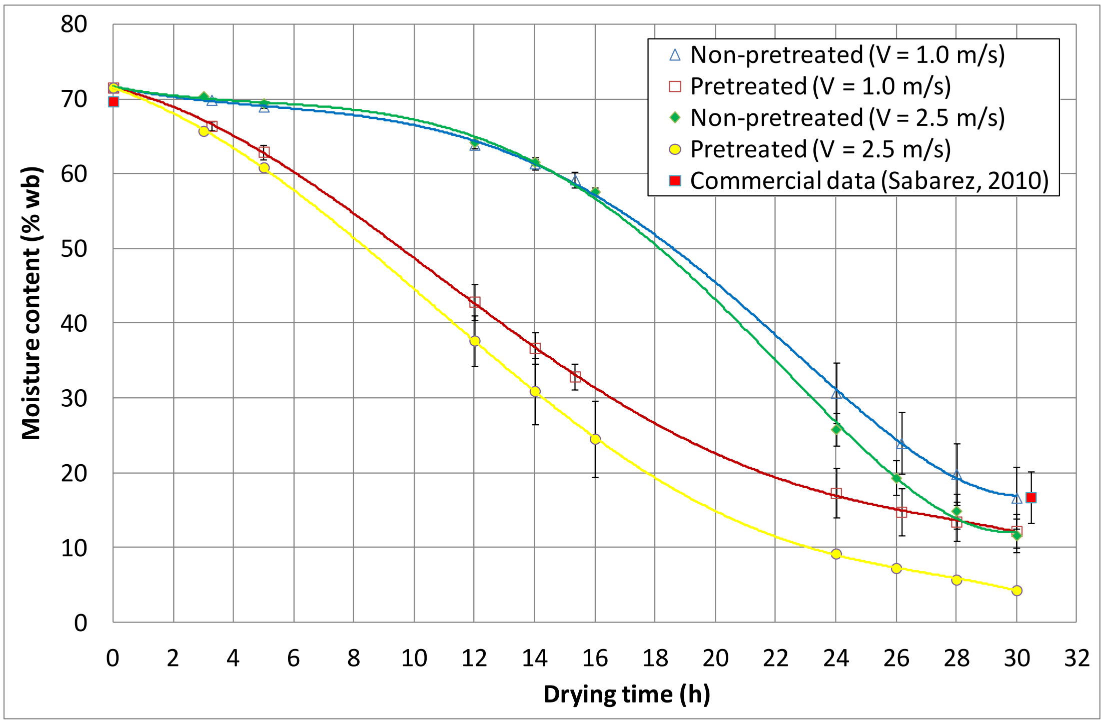


Figure 17. Drying kinetics of plums (variety: GF698; 2015 fruit harvest season) non-pretreated and pretreated with ultrasound in oil emulsion under simulated industrial counter-flow tunnel drying at two air velocity levels. Pretreatment conditions (2% ethyl oleate in tap water emulsion, 25°C for 10 min), Ultrasound conditions (Power=460 W; Frequency=40 kHz), Drying conditions (T=55-75°C; RH=35-15%; t=30 h).

A number of laboratory drying experiments were conducted for the 2015 fruit harvest season to mimic the industrial tunnel drying of plums both in counter-flow and parallel-flow modes of operation. Figure 17 shows the drying kinetics of non-pretreated and pretreated plums dried under simulated counter-flow drying conditions (i.e., temperature & relative humidity) at two air velocities. Under the simulated counter-flow drying conditions at low air velocity (1 m/s), it took about 28 hours to dry non-pretreated fresh plums (with 71% moisture) down to 20% moisture, while drying of plums pretreated with ultrasound in oil emulsion took only 21 hours, a 22% (about 7 hours) reduction in total drying time. In the commercial drying of plums under similar counter-flow drying conditions, the total drying time was found to be about 30 hours as reported in a previous study (Sabarez, 2010). On the other hand, the effect of ultrasound-based oil emulsion pretreatment was observed to be much greater at higher air velocity (2.5 m/s) under the same counter-flow drying conditions. It took about 26 hours to dry non-pretreated plums under counter-flow drying conditions at 2.5 m/s air velocity and just about 18 hours for the pretreated plums, indicating that drying of plums pretreated with ultrasound oil emulsion resulted in a 31% (about 8 hours) reduction in drying time compared to the non-pretreated plums. The results indicate that the pretreatment is more effective at higher air velocity under the conditions investigated. The trend could be due to the rate-controlling mechanism predominant at a certain condition. Probably, at low air velocity the moisture loss process may be limited by the maximum evaporation potential (i.e., external moisture transfer from the fruit surface to the drying air). At higher air velocity, the rate of moisture loss may be controlled by the rate of water diffusion across the skin layer. Hence, modifying the skin layer permeability to moisture through pretreatment further enhanced the drying process.

In general, the results indicate that the ultrasound in oil emulsion pretreatment has still significantly affected the drying process (i.e., in terms of the overall reduction in total drying time) under the simulated industrial scale counter-flow drying conditions, consistent with the results obtained under constant drying conditions (small scale experiments). The observed reducing effect of pretreatment under the industrial counter-flow drying conditions as compared with the constant drying condition experiments is consistent with the effect of drying air temperature for both scenarios. It should be kept in mind that effect of pretreatment is maximised at low temperatures (i.e., below 60°C). The plums dried at counter-flow drying conditions were exposed to changing temperature with time, in which the fruit were subjected for a certain period of time to much higher temperature (above 60°C).

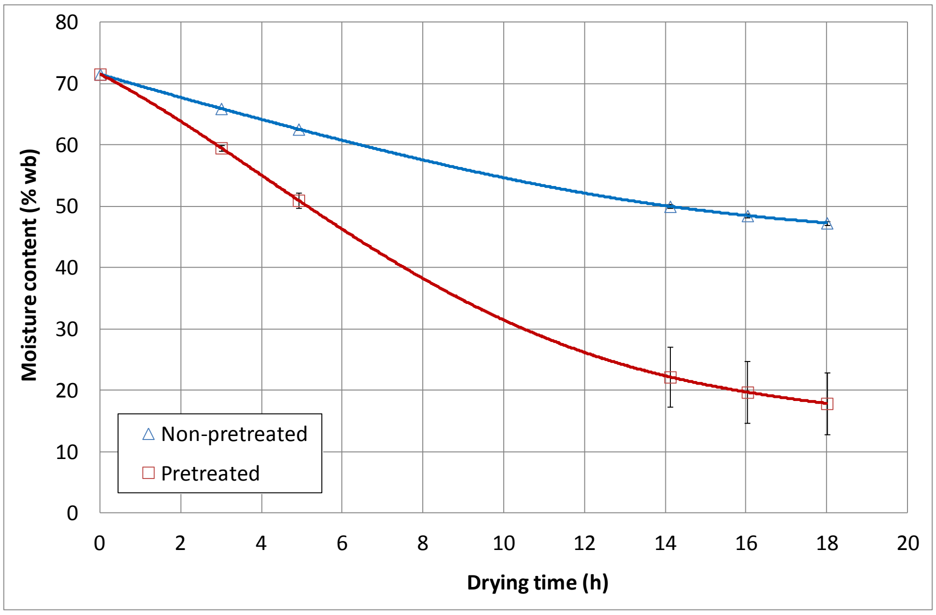


Figure 18. Drying kinetics of plums (variety: GF698; 2015 fruit harvest season) non-pretreated and pretreated with ultrasound in oil emulsion under simulated industrial parallel-flow tunnel drying. Pretreatment conditions (2% ethyl oleate in tap water emulsion, 25°C for 10 min), Ultrasound conditions (Power=460 W; Frequency=40 kHz), Drying conditions (T=67-55°C; RH=23-35%; V=2.5 m/s; t=18 h).

Figure 18 shows the changes in moisture content with time for the non-pretreated and pretreated plums during drying under simulated parallel-flow drying conditions (at 2.5 m/s air velocity). The results indicate a significant effect of ultrasound-based oil emulsion pretreatment. It can be observed that drying of plums for 18 hours under simulated parallel-flow conditions resulted in moisture content of 20% for the pretreated samples whereas the moisture content of the non-pretreated samples was still around 47% for the same drying time and conditions. It should be noted that these simulated parallel-flow drying experiments were carried at a much lower temperature range in comparison to the drying conditions typical in industrial parallel-flow drying operation. The intent was mainly to demonstrate the effect of pretreatment at dynamically changing drying conditions, particularly from high to low temperature condition (i.e., similar trend to the industrial parallel-flow drying condition), but at a much lower temperature range as the use of higher drying temperature (above 70°C) has been demonstrated to significantly reduce the impact of pretreatment in enhancing the drying process. In addition, it is the intention to implement the application of pretreatment at industrial scale under low temperature drying condition for reduced energy consumption with better product quality attributes. In the current commercial drying of plums under the parallel-flow conditions, typical drying process are carried out at temperature range from 85°C to 70°C and could take about 18 hours to complete one drying cycle (i.e., down to final moisture content of about 20%) (Sabarez, 2010). This commercial drying time is similar to the drying time obtained for the pretreated plums dried under the simulated parallel-flow conditions, but a lower temperature range (67-55°C), with the enhancement of the drying process complimented by the application of the pretreatment (i.e., significant reduction in energy consumption and better quality products).

Further experiments under the simulated counter-flow drying conditions were conducted to assess the impact of ultrasound-based oil emulsion pretreatment in enhancing the drying process of plums from different harvest periods (i.e., degree of fruit maturity at harvest). It was postulated that the effectiveness of any pretreatments designed to disrupt the waxy skin layer for intensifying the drying process could also be dependent on the harvest periods of the fruit (or degree of fruit maturity at harvest) due to the natural variations in the amount of waxes deposited on the fruit surface. Waxes deposited on the fruit surface are known to be hydrophobic in nature, which represent an efficient barrier to water movement (Bain and McBean, 1967). Sabarez (1998) found a significant difference of the effect of dipping oil pretreatment in the drying process of plums obtained from two different harvest seasons (1996 & 1997). The author attributed the result to the amount of waxes deposited on the fruit surface, as it was noted that in the 1997 season plums were matured under near-drought conditions. According to McBean et al., (1967), these environmental conditions would result in developing a relatively heavy layer of waxes on the fruit surface. Using an electron microscopy (SEM), Bain and McBean (1969) showed that the generation of wax layer in the plum skin increased with maturity.

Figure 19 depicts the drying kinetics of non-pretreated and pretreated plums obtained from two extreme harvest periods (i.e., early & late harvest) in 2015 fruit season dried under simulated counter-flow drying conditions. There was no significant difference of the effect of ultrasound-based oil emulsion pretreatment in drying of plums obtained from the early and late harvest, although the fruit samples from the late harvest were found to have much lower moisture content (65%) compared to the fruit samples from early harvest (71%). This suggests that the ultrasound-based oil emulsion pretreatment is effective under the conditions investigated in disrupting the waxy skin layer regardless of the amount of wax present in the fruit surface. Hence, the application of ultrasound oil emulsion pretreatment makes the drying process more consistent regardless of maturity and seasonal variability. It should be noted that the waxy skin layer of plums has been demonstrated in previous studies to provide a significant barrier to moisture transfer during the drying process and that the amount varies between harvest seasons and ripening stages (harvest time).

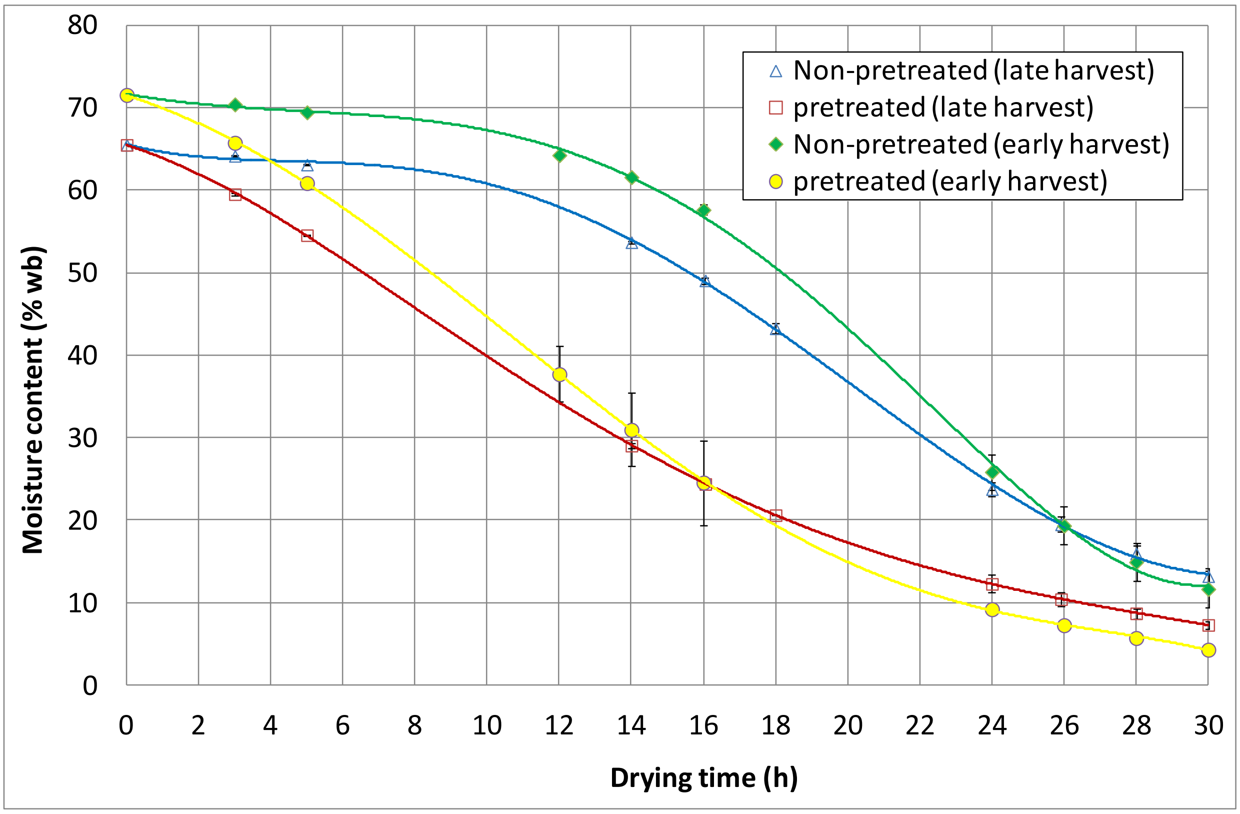


Figure 19. Drying kinetics of plums (variety: GF698; 2015 fruit harvest season) non-pretreated and pretreated with ultrasound in oil emulsion under simulated industrial counter-flow tunnel drying at two harvest times. Pretreatment conditions (2% ethyl oleate in tap water emulsion, 25°C for 10 min), Ultrasound conditions (Power=460 W; Frequency=40 kHz), Drying conditions (T=55-75°C; RH=35-15%; t=30 h).

The findings from these experiments have demonstrated a significant effect of the ultrasound-based oil emulsion pretreatment in enhancing the drying process under the industrial scale drying conditions for both tunnel configurations, suggesting the scalability of the process. It also shows that the effect of pretreatment is dependent on the levels of drying air velocity and progressively decreases as the drying temperature increases, consistent with the results found under constant drying conditions (small scale experiments). In addition, these findings reveal that ultrasound-based oil emulsion pretreatment is effective under the conditions investigated to enhance the drying process and makes the drying process more consistent regardless of the amount of wax in the fruit surface (i.e. fruits harvested at various time periods and seasons).

Recommendations

This research has demonstrated that ultrasound-based pretreatment is a highly effective means of enhancing low temperature drying of plums resulting in shorter drying time and better retention of product quality attributes. The work has provided invaluable insights into the effects of operational parameters for efficient application of the new concept and the mechanisms in which the ultrasound-based pretreatment enhances the drying process of plums. This offers a promising non-thermal means of intensifying the gentle drying of plums for efficient and cost-effective processing and safe operation to produce premium quality product.

It is therefore recommended that the industry builds upon the outcomes of this research in bringing the new ultrasound-based pretreatment concept to industrial scale operations. The commercial practice of washing fresh fruit with ambient water prior to drying would provide a relatively easy way to incorporate the pretreatment procedure into the current commercial operations. However, there are still technological challenges to overcome in order to strengthen its application and fully realise the successful adoption of the technology in industrial practice, including:

- Development of a design concept and building a pilot-scale prototype of the ultrasound-based pretreatment approach for proof of concept testing and optimisation in commercial operations and techno-economic evaluation (cost-benefit analysis) of the technology to assess its scalability and viability for commercial readiness
- Explore the potential of eco-friendly and cost effective approaches for sustainable low temperature drying of plums (e.g., solar drying technology) and the integration of the ultrasound-based pretreatment technology for drying intensification
- Study the changes on the quality attributes (i.e., rehydrability & pitting efficiency, antioxidant capacity, vitamin C, colour, etc) of the ultrasound-based pretreated dried plums during long storage (i.e., under the storage conditions typical in commercial practice)

The findings from the recommended further work would establish a strong basis for the successful development and implementation of the ultrasound-based pretreatment technology at industrial scale operations, enhancing the profitability and long term sustainability of the Australian dried prune industry. It is also anticipated that the pretreatment approach could easily be applied to enhance the drying process of other fruits and vegetables having waxy skin layer (e.g., grapes, berries, peas, tomatoes, etc), providing further benefits to other horticultural industries.

Scientific Refereed Publications

None to report.

Intellectual Property/Commercialisation

The combined application of ultrasound and oil emulsion pretreatment to enhance the drying process of waxy fruits and vegetables is a new concept and has been demonstrated in the laboratory to be highly effective. However, in order to realise this novel approach into commercial IP, further work is necessary to design and develop a pilot prototype of the new ultrasound-based pretreatment method to demonstrate its scalability and viability in commercial operations.

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Appendices

Appendix 1. Milestones Reports.

A1.1. Milestone report No 102.

Project Milestone Report Template

Project Code and Title	DP12001 – Ultrasonic drying of horticultural food products
Milestone Number	102
Due Date	1 July 2013
Author	Henry Sabarez
Service Provider	CSIRO Animal, Food and Health Sciences
Milestone Description	Laboratory ultrasonic drying system developed and evaluated. IP arrangements in place.
Achievement Criteria	Progress report submitted to HAL. IP arrangements finalised and in place. Revised schedule 2 signed by both parties.

Summary

The traditional process of drying prunes is an energy-intensive operation that imparts significant alterations in the nutritional and functional attributes of the fruit. This is primarily due to the fruit's exposure to high temperatures or long drying times. Energy consumption is a major concern for industrial drying operations, not only due to the increasing cost and scarcity of fuel. Environmental concerns are at the forefront of industry priorities, and it is understood that energy consumption needs to be addressed to reduce greenhouse gas emissions. This is coupled with an increasing consumer demand for healthy and high-quality processed foods. There is significant interest in the industry to develop innovative drying approaches that will accelerate the drying process, thereby increasing throughput, and reducing energy consumption without compromising the quality of dried products.

This project builds on CSIRO's previous strategic work to develop and optimise the application of ultrasound technology, which aims to demonstrate the technological feasibility of this new drying concept for efficient and sustainable drying of prunes. In general, all of the achievement criteria envisaged in milestone 102 have been met. This report summarises the progress of the activities undertaken in this phase of the project.

A laboratory ultrasonic drying system was further developed and modified to suit the drying experiments of prunes. In this setup, ultrasonic energy is transmitted airborne to the drying surface of the product, allowing the material to be dried without direct contact with the ultrasonic vibrating element. This setup enables drying experiments in conventional drying conditions, combined with ultrasonics at different process parameters. An ultrasonic pre-treatment setup was also developed to allow for the treatment of fruit samples (i.e. prior to drying) in an aqueous solution at various sonication times, temperatures and ultrasonic conditions (i.e. ultrasonic frequencies and power levels).

The systems were evaluated by conducting a series of drying experiments using fresh plum samples obtained from the industry collaborators in Cobram (Vic) and Darlington Point (NSW). The application of ultrasonics was found to have a significant effect in terms of enhancing the drying process, depending on the ultrasonic parameters and drying conditions. In particular, the results from the preliminary drying tests reveal that the ultrasonic pre-treatment in an aqueous dipping solution significantly reduced the overall drying time of up to 54% in comparison with those samples dried without pre-treatment, depending on the ultrasonic pre-treatment and drying conditions. The antioxidant capacity (measured by the oxygen radical absorbing capacity or ORAC assay) and vitamin C retention were significantly higher with lighter colour for the dried samples ultrasonically pre-treated compared with the non pre-treated samples dried at different drying conditions. Also, the antioxidant capacity levels of the dried plum samples were found to be significantly higher (up to 56%) compared with the fresh plum samples. These suggest that the drying process enhances the

bio-availability of the health-promoting components in the fruit with the magnitude of influence depends on the pre-treatment and drying conditions.

Progress since last milestone report

A laboratory ultrasonic drying system was further developed and modified to suit the drying experiments of prunes. In this setup, ultrasonic energy is transmitted airborne to the drying surface of the product, allowing the material to be dried without direct contact with the ultrasonic vibrating element. This setup enables drying experiments in conventional drying conditions, combined with ultrasonics at different process parameters. An ultrasonic pre-treatment setup was also developed to allow for the treatment of fruit samples (i.e. prior to drying) in an aqueous solution at various sonication times, temperatures and ultrasonic conditions (i.e. ultrasonic frequencies and power levels).

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The IP sharing arrangement between CSIRO and HAL is being finalised and a revised schedule 2 is due very soon for sign off for both parties.

Communication/Extension Activities

• A progress report was submitted in May 2013 to HAL's communication portfolio for publication in the Prune Industry Advisory Committee Annual Report 2012/13.
• The findings for this phase of the project will be presented at the Australian Prune Industry Association (APIA) conference to be held in Sep/Oct 2013 to provide a forum for discussion on the direction and activities of the project.
• Participation/presentation at the International Prune Industry (IPA) conference to be held in Canberra in November 2013.

Commercialisation and Intellectual property issues

The documentation of the IP sharing arrangement between CSIRO and HAL is currently being finalised.

Next Steps

The next major activities will involve preliminary proof-of-concept ultrasonic drying trials for the 2014 fruit harvest season. A series of laboratory drying experiments will be conducted at different process conditions to explore and develop a better understanding of the effects of ultrasound on the drying kinetics and product functional/nutritional attributes. A number of ultrasonic parameters, including power levels, frequencies and sonication times will be investigated under a matrix of drying conditions (i.e. temperature, airflow & humidity) in terms of drying performance (i.e. drying kinetics, drying time, energy efficiency) and on the concomitant impact on product functional and nutritional attributes (i.e. rehydrability, colour, microstructure, vitamin C, antioxidant activity). The results of the *drying trials from the 2014 fruit season will be used for fine-tuning of a range of experimental drying variables for the 2015 fruit season experiments.*

Other Issues

No further issues.

Attachments

A1.2. Milestone report No 103.

Project Milestone Report Template

Project Code and Title	DP12001 – Ultrasonic drying of horticultural food products
Milestone Number	103
Due Date	30 November 2013
Author	Henry Sabarez
Service Provider	CSIRO Animal, Food and Health Sciences
Milestone Description	Mid-term review – Stop/Go point
Achievement Criteria	Progress review and decision point. Mid-term review report.

Summary

The inclusion of Milestone 103 (Stop/Go decision point) was designed to provide the Australia Prune Industry the opportunity to review the mid-term progress of the project. A summary report of the progress of the project and further details of the experimental results were provided to the industry for reviewing. Subsequently, the industry's Project Reference Group has advised for the project to continue into the next stage.

Progress since last milestone report

The inclusion of Milestone 103 (Stop/Go decision point) was designed to provide the Australia Prune Industry the opportunity to review the mid-term progress of the project. A report summarises the progress of the activities undertaken in the 1st phase of the project that is subject to this mid-term review by the industry has been submitted to HAL in the last milestone reporting (Milestone 102). It should be noted that all of the achievement criteria envisaged in the last Milestone 102 have been met.

A copy of the Milestone 102 report was also submitted to the industry's Project Reference Group for their assessment and to provide a basis to make their decision to go ahead or not into the next stage of the project. In addition, further information on the details of the results for the 2013 fruit harvest season experiments was provided to the Project Reference Group (attached).

The HAL Portfolio Manager was subsequently advised that the Project Reference Group has had no concerns about the progress of the project and recommended for the project to continue into the next stage.

Communication/Extension Activities

• A progress report (Milestone 102) and further details of the experimental results for 2013 fruit harvest season were provided to the industry's Project Reference Group for reviewing.
• A number of telephone conversations were held with the industry's executives (Malcolm Taylor and Grant Delves) to further discuss the details of the progress of the project.

Commercialisation and Intellectual property issues

The IP sharing arrangement between CSIRO and HAL has been amended and finally signed by both parties.

Next Steps

The next major activities (Milestone 104) will involve preliminary proof-of-concept ultrasonic drying trials for the 2014 fruit harvest season. A series of laboratory drying experiments will be conducted at different process conditions to explore and develop a better understanding of the effects of ultrasound on the drying kinetics and product functional/nutritional attributes. A number of ultrasonic parameters, including power levels, frequencies and sonication times will be investigated under a matrix of drying conditions (i.e. temperature, airflow & humidity) in terms of drying performance (i.e. drying kinetics, drying time, energy efficiency) and on the concomitant impact on product functional and nutritional attributes (i.e. rehydrability, pitting efficiency, colour, microstructure, vitamin C, antioxidant activity). The results of the drying trials from the 2014 fruit season will be used for fine-tuning of a range of experimental drying variables for the 2015 fruit season experiments.

Other Issues

No further issues.

Attachments

A1.3. Milestone report No 104.

Project Milestone Report Template

Project Code and Title	DP12001 – Ultrasonic drying of horticultural food products
Milestone Number	104
Due Date	01 July 2014
Author	Henry Sabarez
Service Provider	CSIRO Food, Nutrition & Bioproducts
Milestone Description	Preliminary laboratory drying trials conducted for 2014 fruit harvest season
Achievement Criteria	Progress report submitted to HAL

Summary

A three year study, aims to develop and optimise the application of ultrasound technology for efficient and sustainable drying of prunes, is on track to achieving its objectives into the second year of research. In particular, the achievement criteria agreed in this milestone (MS104) have been successfully met. This report summarises the progress of the activities undertaken in this phase of the project, the communication activities that have been carried out since the last milestone report, and the next major activities to be undertaken.

Results from the proof-of-concept preliminary drying trials have shown significant reductions in the overall drying time (i.e. up to 57%) with the application of ultrasound pre-treatment in oil dipping emulsion, with better retention in the antioxidant capacity and vitamin C and lighter in colour of the dried product. The investigations also reveal that the impact of the ultrasonic-based pre-treatment in terms of reducing the drying time varies significantly with drying conditions and the ultrasonic parameters. In particular, the ability of the combined ultrasound and oil emulsion pre-treatment to improve the efficiency of the drying process appears to be maximised when using lower drying temperature.

A number of drying trials for the 2014 fruit harvest season were further carried out to demonstrate the scalability of the pre-treatment and drying processes and the impact of such large scale experiments (i.e. ~15 times larger than the small scale experiments) on the rehydrability and pitting of dried prunes under commercial conditions, and the corresponding changes in the antioxidant activity levels. The results from the large scale experiments showed about 59% reduction in the overall drying time with lighter colour and higher antioxidant capacity for the pre-treated dried samples. This is consistent with the results from the small scale experiments, suggesting the scalability of the process. In addition, no significant differences in the pitting efficiency between the control and the pre-treated samples were observed.

Progress since last milestone report

A number of laboratory drying experiments were initially undertaken for the 2013 fruit harvest season to test and evaluate the performance of the ultrasonic drying system. In particular, the results from these drying trials have shown that the ultrasonic pre-treatment in an aqueous dipping solution significantly reduced the overall drying time of up to 54% in comparison with those samples dried without pre-treatment, with better retention of the antioxidant capacity (measured by the oxygen radical absorbing capacity or ORAC assay) and vitamin C and lighter colour of the pre-treated dried samples. Under the conditions investigated, the combination of ultrasound and oil emulsion pre-treatment was found to have the highest effect in terms of enhancing the drying process compared *with ultrasound alone or oil emulsion alone pre-treatments. Also, the results from these initial trials suggest that the effect of ultrasound pre-treatment in the drying process and product quality attributes depends on the drying conditions and ultrasonic parameters.*

A suite of laboratory drying experiments were further conducted for the 2014 fruit harvest season to investigate and explore the effect of ultrasound pre-treatment on the drying process and product quality attributes under different drying conditions and ultrasound parameters. Preliminary short drying experiments (i.e. normally up to 5 hours) were carried out to initially assess/screen the impact of a range of process variables at different levels. Depending on the drying conditions, it would normally take of up to 40 hours to complete one drying cycle for prunes. In addition, fresh plums are only available for 3-4 weeks in a year and usually won't last long under cold storage conditions. Therefore, the screening approach employed in this work has provided the ability to maximise the number of experiments to be undertaken. A similar approach has been reported in a number of drying studies that can be found in the literature.

The results from the proof-of-concept drying trials reveal that the effect of ultrasonic pre-treatment varies significantly with the subsequent drying conditions. In particular, the ability of the combined ultrasonic and oil emulsion pre-treatment to improve the efficiency of the drying process appears to be maximised when using lower drying temperature and that the effect of pre-treatment progressively decreases as the drying temperature increases. For example, drying at 60ºC resulted in 57% reduction in the overall drying time with the application of pre-treatment while drying at 70ºC and 80ºC with the pre-treated samples resulted in 28% and 13% reduction in the overall drying time, respectively. This indicates that with the application of pre-treatment, drying of prunes can be carried out at lower drying temperature while still achieving faster drying rates (i.e. resulting in increased throughput and reduced energy consumption with better quality of the product). The relative humidity of the drying air is another important drying condition that significantly affects the drying process of prunes. A suite of experiments were undertaken to examine the effect of ultrasound in oil emulsion pre-treatment at two different levels of drying air relative humidity (15% & 30%), that can be found typically in industrial tunnel drying conditions. The results from these drying trials show that the effect of pre-treatment is slightly better at higher drying relative humidity condition, under the range of conditions investigated. Further experiments are envisaged to be carried out in the next fruit harvest season for other drying relative humidity conditions and various levels of drying air velocity. It should be noted that an investigation on the effects of various levels of drying conditions is important in terms of applying the results to large scale operations, as the drying conditions (i.e. particularly temperature and relative humidity) at industrial tunnel dryers are systematically changing with drying time and position in the drying tunnel.

The results from the drying trials also unveil the impact of ultrasonic pre-treatment parameters (i.e. sonication time, ultrasonic frequency & emulsion recycling) on the drying process. Three levels of pre-treatment sonication time (1, 5 & 10 min) were studied using the best pre-treatment conditions (i.e. combined ultrasound & oil emulsion, ultrasonic frequency) initially established in the previous experiments. The samples were then subsequently dried at 60ºC. No significant differences in the drying time between samples pre-treated for 1 min and 5 min were observed. The samples pre-treated for 10 min showed a slightly shorter drying time compared with the samples pre-treated with the other two sonication times. This finding suggests that a shorter pre-treatment time could be employed while still achieving an effective pre-treatment. A shorter pre-treatment time is ideal as it usually requires a large throughput capacity at industrial scale operation for the technology to be commercially viable. Moreover, there was little effect of ultrasonic frequencies tested (40 kHz & 270 kHz) in terms of reducing the drying time. No significant differences in drying time were found for re-using the emulsion solution pre-treatment for at least 3 times.

A number of drying trials for the 2014 fruit harvest season were further carried out to demonstrate the scalability of the pre-treatment and drying processes, and the impact of such large scale experiments on the rehydrability and pitting of dried prunes at industrial scale conditions, and the corresponding changes in microstructure and antioxidant activity levels. The large scale experiments were undertaken using about 2.6 kg of fresh plums per experimental treatment (~15 times larger than the small scale experiments). Two sets of large scale experiments (i.e.3 replicates each set), *including without pre-treatment (control) and with pre-treatment (i.e. using the combined ultrasound and oil emulsion) were carried out and the samples were then subsequently dried at 60ºC until the final moisture content reached to the desired level (~20%). The dried samples were sent to Country Foods Pty Ltd (Young, NSW) for rehydration and pitting under commercial conditions.*

The results from the large scale experiments showed about 59% reduction in the overall drying time with the application of pre-treatment. This is consistent with the results from the small scale experiments (~150g per experimental treatment), suggesting the scalability of the process. No significant differences in the pitting efficiency between the control and the pre-treated samples were observed. In addition, the pre-treated samples were found to have a lighter colour with higher antioxidant activity level (~50% more) compared with the untreated samples, corroborating with the previous results from the small scale experiments. The microscopy analysis of both untreated and pre-treated partially-dried samples, employing an environmental scanning electron microscopy (ESEM) technique shows more disruptions of the waxy skin layer for the pre-treated fruit samples than the control samples. It should be noted that the waxy skin layer of prunes has been demonstrated in previous studies to provide a significant barrier to moisture transfer during the drying process. The disruption of the waxy skin layer with the application of pre-treatment is consistent with the observed significant reduction in drying time as a consequence of improved moisture transfer across the waxy skin layer of the fruit.

Communication/Extension Activities

- *A progress report was submitted in May 2014 to HAL's communication portfolio for publication in the Prune Industry Advisory Committee Annual Report 2013/14.*
- *A number of discussion/meetings were held with Sunsweet Growers Inc (USA) for their potential participation in co-investing the next phase of the project (i.e. commercial development and evaluation of the ultrasonic pre-treatment technology for prunes).*
- *A number of telephone conversations and industry visits were held with the industry's executives and industry members to further discuss the progress and direction of the project.*

Commercialisation and Intellectual property issues

No further issues.

Next Steps

The next major activities (Milestone 105) will involve further drying trials for the 2015 fruit harvest season. The results of the drying trials from the 2013 and 2014 fruit harvest seasons will be used to design and plan a range of experimental conditions for further testing in the next fruit harvest season experiments. In addition, these experiments will likely to include drying experiments under simulated conditions typical in industrial scale tunnel drying system (i.e. both in parallel-flow & counter-flow configuration).

Other Issues

No further issues.

Attachments

A1.4. Milestone report No 105.

Project Milestone Report Template

Project Code and Title	DP12001 – Ultrasonic drying of horticultural food products
Milestone Number	105
Due Date	30 November 2014
Author	Henry Sabarez
Service Provider	CSIRO Food and Nutrition Flagship
Milestone Description	Second year progress report
Achievement Criteria	Progress report summarising the progress of 2 years

Summary

The inclusion of Milestone 105 (i.e. second year mid-term progress review) was designed to provide the Australia Prune Industry the opportunity to review the second year mid-term progress of the project. A report summarises the progress of the activities undertaken in the second year of the project that is the main subject to the mid-term review by the industry has been submitted to HAL in the last milestone reporting (Milestone 104) in June 2014. It should be noted that all of the achievement criteria envisaged in the last Milestone 104 have been met. In addition, a presentation on the progress of the project and further details of the experimental results for 2014 fruit harvest season were presented at the industry's annual conference for reviewing and further discussion on the direction of the project. The industry was generally happy with the progress for the past 2 years and for the project to continue into the final stage of activities. This report summarises the progress of the project for the past 2 years.

Progress since last milestone report

A three year study, aims to develop and optimise the application of ultrasound technology for efficient and sustainable drying of prunes, is progressing well and all of the achievement criteria envisaged in the past 2 years have been successfully met.

A laboratory ultrasonic system was successfully developed to allow for the treatment of fruit samples (i.e. prior to drying) in an aqueous solution at various sonication times, temperatures and ultrasonic conditions (i.e. ultrasonic frequencies and power levels). The system was evaluated by conducting a series of drying experiments using 2013 and 2014 fresh plum samples obtained from the industry collaborators in Cobram (Vic) and Darlington Point (NSW).

Results from the preliminary laboratory drying experiments undertaken for the 2013 fruit harvest season have shown the ultrasonic pre-treatment to have significant effect in terms of enhancing the drying process with better retention of the nutritional and functional properties of the product. In particular, the results reveal that the ultrasonic pre-treatment in oil emulsion significantly reduced the overall drying time of up to 54% in comparison with those samples dried without pre-treatment, depending on the ultrasonic pre-treatment and drying conditions. The antioxidant capacity (measured by the oxygen radical absorbing capacity or ORAC assay) and vitamin C retention were significantly higher with lighter colour for the dried samples ultrasonically pre-treated compared with the non pre-treated samples. Also, the antioxidant capacity levels of the dried plum samples were found to be significantly higher (up to 56%) compared with the fresh plum samples. These suggest that the drying process may enhance the bio-availability of the health-promoting components in the fruit with the magnitude of influence depends on the pre-treatment and drying conditions.

A suite of laboratory drying experiments were further conducted for the 2014 fruit harvest season to investigate the effect of ultrasound pre-treatment on the drying process and product quality attributes *under different drying conditions. The results from these drying trials reveal that the effect of ultrasonic pre-treatment varies significantly with the subsequent drying conditions. In particular, the ability of the combined ultrasonic and oil emulsion pre-treatment to improve the efficiency of the drying process appears to be maximised when using lower drying temperature and that the effect of pre-treatment progressively decreases as the drying temperature increases. For example, drying at 60ºC resulted in 57% reduction in the overall drying time with the application of pre-treatment while drying at 70ºC and 80ºC with the pre-treated samples resulted in 28% and 13% reduction in the overall drying time, respectively. This indicates that with the application of pre-treatment, drying of prunes can be carried out at lower drying temperature while still achieving faster drying rates (i.e. resulting in increased throughput and reduced energy consumption with better quality of the product). Further experiments are envisaged to be carried out in 2015 fruit harvest season for other drying conditions (i.e. relative humidity & airflow) and ultrasonic parameters.*

A number of drying trials for the 2014 fruit harvest season were further carried out to demonstrate the scalability of the pre-treatment and drying processes, and the impact of such large scale experiments on the rehydrability and pitting of dried prunes at industrial scale conditions, and the corresponding changes in microstructure and antioxidant activity levels. The large scale experiments were undertaken using about 2.6 kg of fresh plums per experimental treatment (~15 times larger than the small scale experiments). Two sets of large scale experiments, including without pre-treatment (control) and with pre-treatment (i.e. using the combined ultrasound and oil emulsion) were carried out and the samples were then subsequently dried at 60ºC until the final moisture content reached to the desired level (~20%). The dried samples were sent to Country Foods Pty Ltd (Young, NSW) for rehydration and pitting under commercial conditions.

The results from the large scale experiments showed about 59% reduction in the overall drying time with the application of pre-treatment. This is consistent with the results from the small scale experiments (~150g per experimental treatment), suggesting the scalability of the process. No significant differences in the pitting efficiency between the control and the pre-treated samples were observed. In addition, the pre-treated samples were found to have a lighter colour with higher antioxidant activity level (~50% more) compared with the untreated samples, corroborating with the previous results from the small scale experiments. The microscopy analysis of both untreated and pre-treated partially-dried samples, employing an environmental scanning electron microscopy (ESEM) technique shows more disruptions of the waxy skin layer for the pre-treated fruit samples than the control samples. It should be noted that the waxy skin layer of prunes has been demonstrated in previous studies to provide a significant barrier to moisture transfer during the drying process. The disruption of the waxy skin layer with the application of pre-treatment is consistent with the observed significant reduction in drying time as a consequence of improved moisture transfer across the waxy skin layer of the fruit.

Communication/Extension Activities

- *A presentation was delivered at the Australian Prune Industry Association conference held in Griffith (NSW) in September 2014 to report on the progress of the project and further discuss on the research direction of the project.*
- *A brief article was submitted in November 2014 to the Industry Development Officer of the Australian Prune Industry Association for publication in the January 2015 edition of the Vine Magazine.*

Commercialisation and Intellectual property issues

No further issues.

Next Steps

The next major activities (Milestone 106) will involve further drying trials for the 2015 fruit harvest season. The results of the drying trials from the 2013 and 2014 fruit harvest seasons will be used to design and plan a range of experimental conditions for further testing in the next fruit harvest season experiments. In addition, these experiments will likely to include drying experiments under simulated conditions typical in industrial scale tunnel drying system (i.e. both in parallel-flow & counter-flow configuration).

Other Issues

No further issues.

Attachments

None.

A1.5. Milestone report No 106.

Horticulture Innovation Australia

Milestone Report

Project Code: DP12001

Project Title: Ultrasonic drying of horticultural products

Milestone Number: 106

Milestone Due Date: 01 July 2015

Research Provider: CSIRO Food & Nutrition Flagship

Project Leader: Dr Henry Sabarez

Report Author: Dr Henry Sabarez

Milestone Description: Laboratory drying trials conducted for 2015 fruit harvest season

Milestone Achievement Criteria: Progress report submitted to HIA Ltd

R&D projects: levy funding
This project has been funded by Horticulture Innovation Australia Limited using the ***Dried Prune Industry*** levy and funds from the Australian Government.

Summary

A three year study, aims to develop and optimise the application of ultrasound technology for efficient and sustainable drying of prunes, is on track to achieving its objectives into the final year of research. In particular, the achievement criteria agreed in this milestone (MS106) have been successfully met. This report summarises the progress of the activities undertaken in this phase of the project.

The main focus of the work in this phase of the project was to conduct laboratory drying trials to investigate the effect of ultrasound-based pre-treatment under simulated conditions typical in industrial scale tunnel drying system in order to assess the scalability of the pre-treatment technology. A number of drying experiments were undertaken to mimic the drying of plums under industrial scale drying conditions, particularly in counter-flow and parallel-flow mode of operations. In addition, the effects of ultrasound-based pre-treatment at two levels of drying air velocity and the time of harvest (fruit samples from early & late harvest) were also studied.

The findings from the drying experiments have demonstrated the ultrasound-based pre-treatment to have significant effect in enhancing the drying process under industrial scale drying conditions for both tunnel configurations suggesting the scalability of the process. It also shows that the effect of pre-treatment is dependent on the levels of drying air velocity and progressively decreases as the drying temperature increases, consistent with the results found under constant drying conditions (as reported in previous milestones). In addition, the findings reveal that ultrasound-based pre-treatment is effective to enhance the drying process regardless of the amount of wax in the fruit surface (i.e. fruits harvested at various time periods and seasons).

Milestone Achievements

The main focus of the work in this reporting period was to investigate the effect of the best pre-treatment condition (i.e. combined ultrasound and oil emulsion as established in previous experiments) on the drying process under simulated conditions typical in industrial scale tunnel drying system. It should be noted that the drying conditions (i.e. particularly temperature and relative humidity) at industrial tunnel dryers are systematically changing with drying time and position in the drying tunnel, depending on the mode of operation. The industrial tunnel dehydrators are currently operated in either counter-flow or parallel-flow mode of operation. In a counter-flow configuration, the drying air is introduced into one end of the tunnel while the trolleys of fresh fruits enter at the other end and each moves in opposite directions. This configuration is characterised by having conditions most conducive to intense heating at the end of the drying cycle when the products are nearly dry and less heating in the early stages. The operation of the parallel-flow tunnel is opposite to that of the counter-flow. The trolleys of fresh fruits and drying air enter at the same end of the tunnel and progress through the tunnel in the same direction. This configuration is characterised by intense heating in the early stages where the products to be dried are still very wet followed by slow drying as the product approaches the cooler end.

A number of laboratory drying experiments were conducted for the 2015 fruit harvest season to mimic the industrial tunnel drying of plums both in the counter-flow and parallel-flow modes of operation. In a simulated counter-flow drying, the drying air temperature was set initially at 55°C then increased linearly until up to 75°C for a total drying time of 30 hours and the corresponding drying air relative humidity was set initially at 35% then linearly decreased as drying progresses until the relative humidity reaches 15%. The selected temperature and relative humidity profiles are representative of the current commercial prune tunnel drying operations (Sabarez, 2010). In addition, under these counter-flow conditions the effects of ultrasound-based pre-treatment at two levels of drying air velocity (1.0 & 2.5 m/s) and the time of harvest (fruit samples from early & late harvest) were studied. For the simulated parallel-flow drying, the drying temperature was set initially at 67°C then decreased linearly down to 55°C whilst the corresponding drying air relative humidity was set initially at 23% and progressively increased to 35%. The drying process under these simulated parallel-flow conditions was carried out for a total drying time of 18 hours.

The results from the drying trials in this phase of the project reveal that the ultrasound-based pre-treatment has still significantly affecting the drying process (i.e. in terms of the overall reduction in total drying time) under simulated industrial scale drying conditions, consistent with the results previously obtained under constant drying conditions (as reported in previous milestones). Under the simulated counter-flow drying conditions at low air velocity (1m/s), it took about 28 hours to dry untreated plums (with 71% moisture) down to 20% moisture, whilst drying of plums pre-treated with ultrasound took only 21 hours, a 22% reduction in total drying time. In the commercial drying of plums under similar conditions, the total drying time was found to be about 30 hours as reported in the previous prune drying project (Sabarez, 2010). Also, the effect of ultrasound-based pre-treatment was observed to be much greater at higher air velocity (2.5m/s) under the same counter-flow drying conditions, indicating that drying of plums pre-treated with ultrasound resulted in 31% reduction in drying time compared to the untreated plums. In addition, there was no significant difference of the effect of ultrasound-based pre-treatment in drying of plums obtained from the early and late harvest, although the fruit samples from the late harvest were found to have much lower moisture content (65%) compared to the fruit samples from early harvest (71%). This suggests that the ultrasound-based pre-treatment is effective in disrupting the waxy skin layer regardless of the amount of wax present in the fruit surface. It should be noted that the waxy skin layer of plums has been demonstrated in previous studies to provide a significant barrier to moisture transfer during the drying process and that the amount varies between harvest seasons and ripening stages (harvest time). On the other hand, the results of the drying experiments under simulated parallel-flow conditions also show a significant effect of ultrasound-based pre-treatment. It can be observed that drying of plums for 18 hours under simulated parallel-flow conditions (at 2.5m/s air velocity) resulted in a moisture content of 20% for the pre-treated samples whereas the moisture content of the untreated samples was still around 47%.

Overall, the findings from the drying experiments have demonstrated the ultrasound-based pre-treatment to have significant effect in enhancing the drying process under industrial scale drying conditions for both tunnel configurations suggesting the scalability of the process. It also shows that the effect of pre-treatment is dependent on the levels of drying air velocity and progressively decreases as the drying temperature increases, consistent with the results found under constant drying conditions (as reported in previous milestones). In addition, the findings reveal that ultrasound-based pre-treatment is effective to enhance the drying process regardless of the amount of wax in the fruit surface (i.e. fruits harvested at various time periods and seasons).

Outputs

- An article submitted for publication in the January 2015 edition of the Vine Magazine.
- A presentation delivered at the Australian Prune Industry Association conference held in Griffith (NSW) in September 2014 to report on the progress of the project and further discuss on the research direction of the project.

Refereed Scientific Publications

None to report.

Outcomes

- Improved competitiveness of the Australian prune industry through the expected cost reduction in the drying process with the application of ultrasound-based pre-treatment.
- New market opportunities with increased market returns for product with high nutritional and functional properties.

Intellectual Property, Commercialisation and Confidentiality

No IP, commercialisation or confidentiality issues or development to report.

Issues and Risks

None to report.

Other Information

No additional information to report.

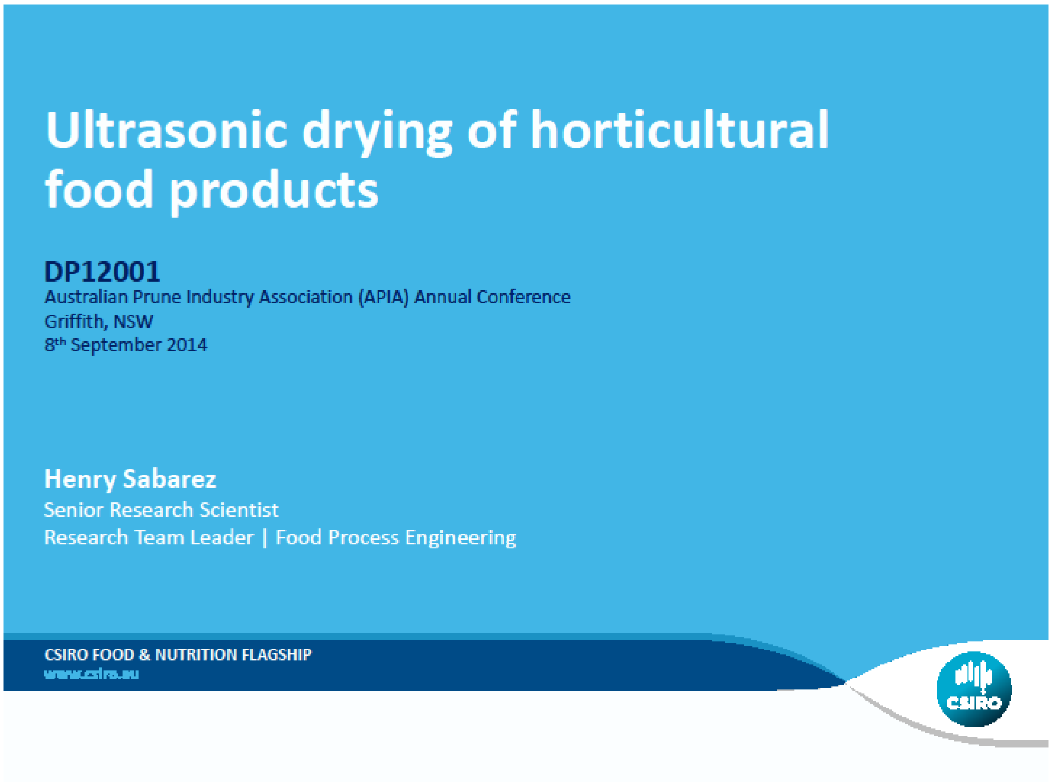
Appendices

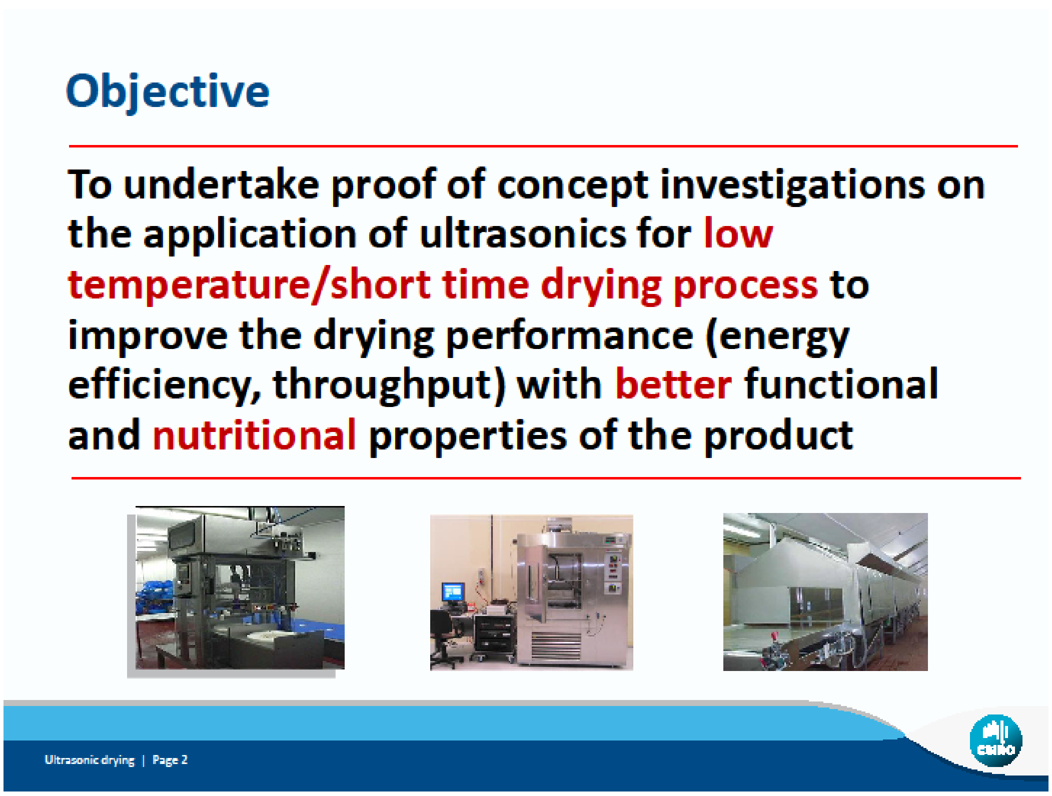
None.

References

Sabarez, H.T., 2010. Improving prune dehydration cost efficiency. Unpublished Report Prepared by CSIRO Food and Nutrition Flagship for Horticulture Australia Limited (HAL), Australia.

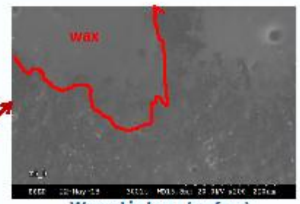
Appendix 2. A progress presentation delivered at the Prune Industry Annual Conference in 2014.



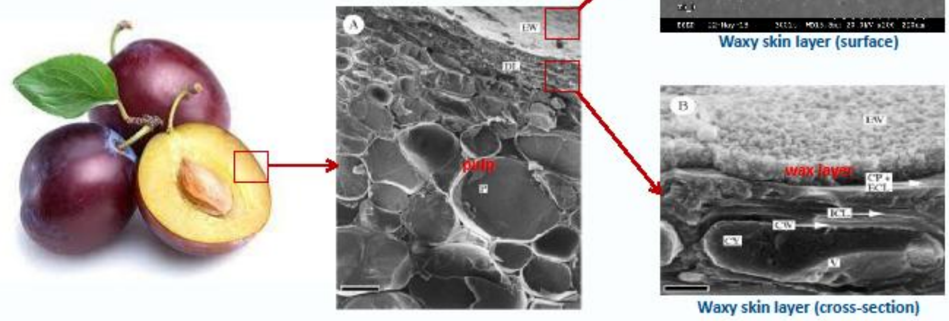


Rationale

- Challenges in drying whole waxy fruits (e.g. plums, berries, grapes)
  - Very slow drying process
  - Naturally covered with wax – barrier to water transfer
- Approaches to disrupt the waxy skin layer
  - Application of pre-treatments
  - Elevated temperature (>70°C: start wax melting)



Waxy skin layer (surface)



Waxy skin layer (cross-section)

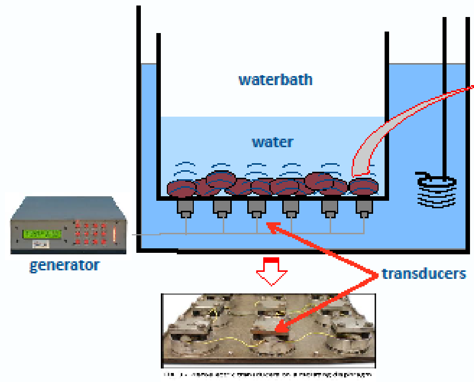
Pre-treatment Technologies

- Chemical/Thermal
  - Fatty acid esters (oil) in alkaline solution (grapes industry), boiling caustic soda, etc
  - Previous studies – marginal effect (~2-4 hours reduction in drying time)
  - Harsh conditions and elevated temperatures
- Physical
  - Superficial abrasion – using abrasive materials to remove the wax
  - Piercing with thin needles
  - Issues of disintegration during pitting & the practicability of the approach

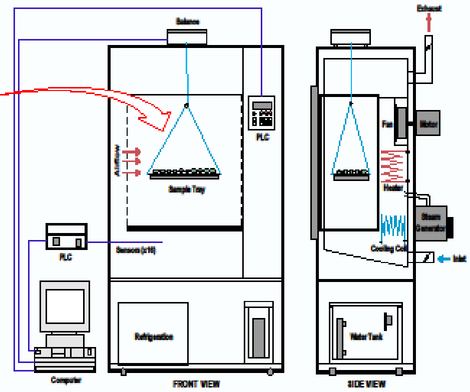
Current Approach

- Physico-chemical (combined oil emulsion & ultrasonic)
  - Oil emulsion – dissociation of wax
  - Ultrasound – physical disruption, stabilise oil emulsion (eliminate emulsifiers), facilitate penetration of oil into the cuticle for effective action
  - Milder pre-treatment conditions & effective drying (i.e. low temp/short time)

Experimental



Experimental pre-treatment setup



Experimental drying setup

- Process Variables
  - Pre-treatment parameters
    Ultrasonic (freq, power, time), Oil (conc, type, recycling)
  - Drying conditions (temp, RH, velocity), Initial MC (season)
- Process Performance
  - Drying kinetics (time, throughput, energy efficiency)
  - Functional (pitting efficiency, rehydrability, colour)
  - Nutritional (antioxidant, vit C)

Application of Ultrasound

Human Hearing

Echo-location
(sonar)

Diagnostic Ultrasound

High Frequency
Low Energy

1 – 10 MHz

- Non-destructive testing
- Medical imaging

Power Ultrasound

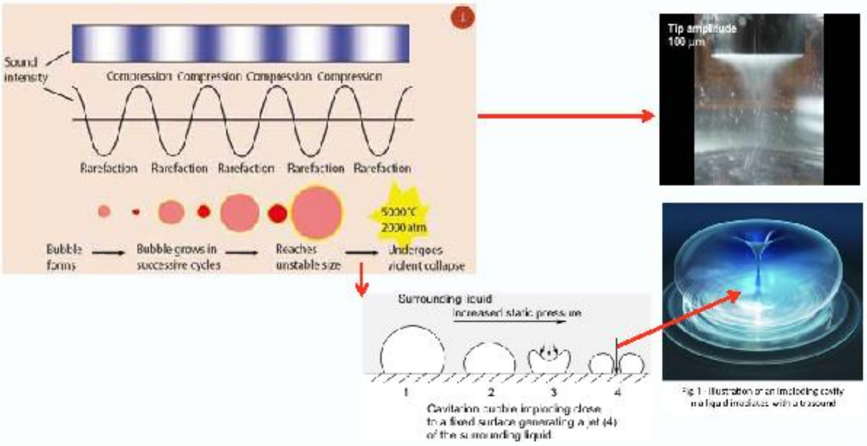
Low Frequency
High Energy

20 – 100 kHz

- Material altering
- Food processing, cleaning

How does the ultrasound work?

(Ultrasound – a sound beyond the limits of human hearing with a frequency >20 kHz)



- Facilitates peeling away of surface wax (mechanical)
- Induces emulsification of oil in water

Pre-treatment conditions: 25°C for 10min
Dipping emulsion: 2% oil in tap water
Ultrasound (US) conditions: frequency & power levels
Drying conditions: T=60°C; Rh=15%; V=2.5m/s
Prune variety: GF698
Harvest season: 2013
Sample size: 160g fresh/drying run

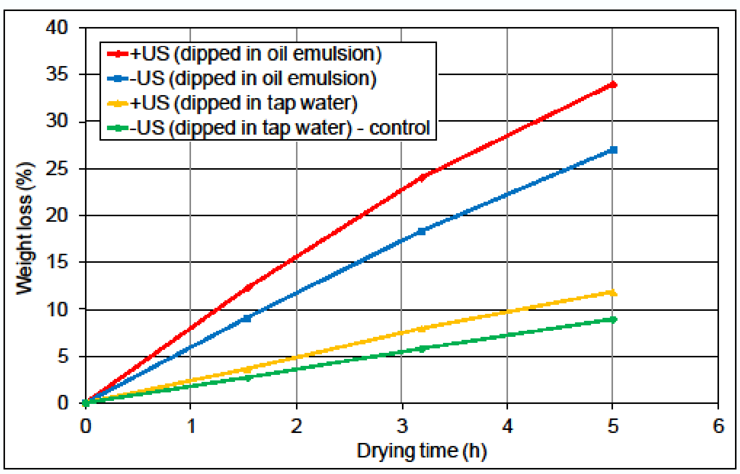
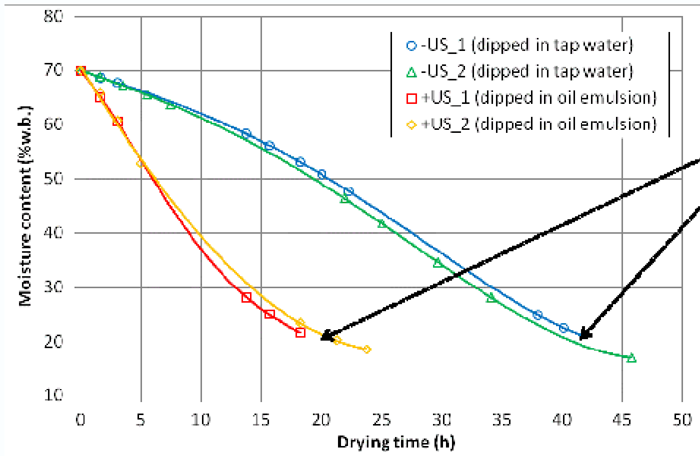


Fig.1. Typical example of the preliminary screening trials undertaken to initially evaluate the effects of different process variables (i.e. drying up to 5 hrs).

Pre-treatment conditions: 25°C for 10min
Dipping emulsion: 2% oil in tap water
Ultrasound (US) conditions: 40 kHz @ 460 W
Drying conditions: T=60°C; Rh=15%; V=2.5m/s
Prune variety: GF698
Harvest season: 2013
Sample size: 160g fresh/drying run



52% reduction (~22h)

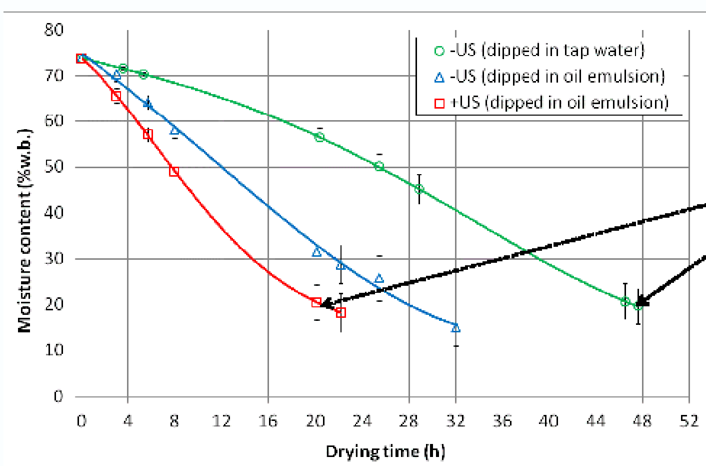
Commercial Dryer:

Dryer No: 8
Configuration: parallel
Setpoint temp: 85°C
Drying time: 20 hrs

Dryer No: 9
Configuration: counter
Setpoint temp: 72°C
Drying time: 37 hrs

Fig.2. Effect of ultrasound/dipping emulsion pre-treatment on plums dried at 60°C air temperature (showing repeatability for 2 replicates).

Pre-treatment conditions: 25°C for 10min
Dipping emulsion: 2% oil in tap water
Ultrasound (US) conditions: 40 kHz @ 460 W
Drying conditions: T=60°C; Rh=15%; V=2.5m/s
Prune variety: 303
Harvest season: 2013
Sample size: 160g fresh/drying run



57% reduction (~27h)

Fig.3. Effect of ultrasound/dipping emulsion pre-treatment on plums dried at 60°C air temperature (for a different prune variety).

Pre-treatment conditions: 25°C for 10min
Dipping emulsion: 2% oil in tap water
Ultrasound (US) conditions: 40 kHz @ 460 W
Drying conditions: T=70°C; Rh=15%; V=2.5m/s
Prune variety: 303
Harvest season: 2013
Sample size: 160g fresh/drying run

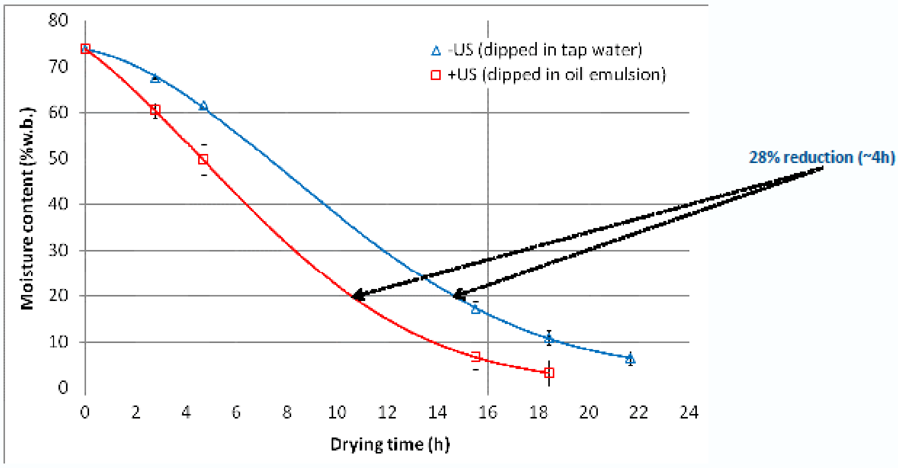
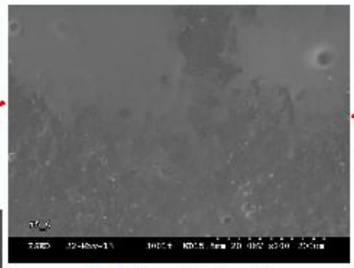


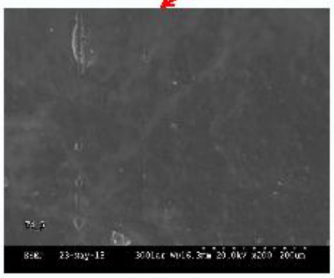
Fig.4. Effect of ultrasound/dipping emulsion pre-treatment on plums dried at a higher air temperature (70°C).

		Moisture content (% w.b.)	Vitamin C (mg/100g dry weight)	Antioxidant (ORAC assay) (T.E. µmol/100g dry weight)
Fresh Plums *(No pre-treatment)*		70.03	3.34	2502.5
Dried (-US) *(Dipped in tap water for 10min) (Drying: T=80ºC for 9h)*		20.37	< 0.13	5098.6
Dried (-US) *(Dipped in tap water for 10min) (Drying: T=60ºC for 40h)*		22.57	< 0.13	4210.2
Dried (+US) *(Dipped in oil emulsion for 10min) (US: frequency & power levels) (Drying: T=60ºC for 18h)*		21.64	0.23	5832.1

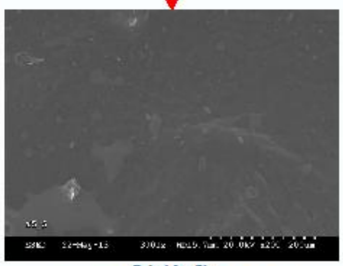
- Drying process may enhance the bio-availability of the health-promoting components in the fruit
- US pre-treatment (short time/low temperature) better retention of VitC & increased AO activity



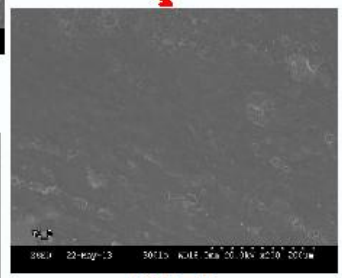
Fresh (no pre-treatment)



Dried for 5h
Drying: T=60°C; Rh=15%; V=2.5m/s
Pre-treatment: dipped in water for 10min
Ultrasound:40 kHz at 460W

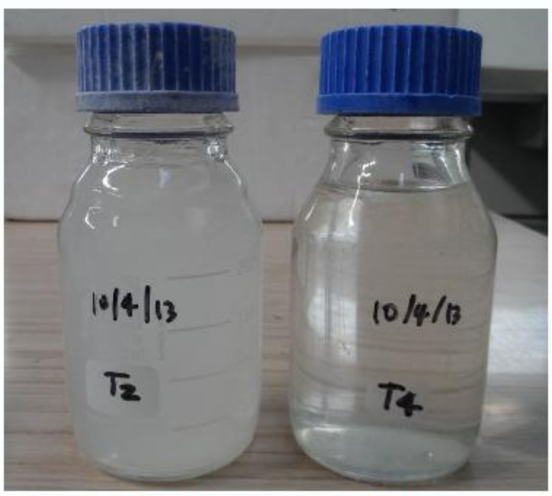


Dried for 5h
Drying: T=60°C; Rh=15%; V=2.5m/s
Pre-treatment: None
Ultrasound: None



Dried for 5h
Drying: T=60°C; Rh=15%; V=2.5m/s
Pre-treatment: dipped in oil emulsion for 10min
Ultrasound: 40kHz at 460W

Ultrasonic drying | Page 13



Pre-treatment	Pre-treatment
Oil in tap water	Oil in tap water
Ultrasound: 40kHz at 460W	Ultrasound: none

Taken after ~5 months storage (i.e. without any further mixing).

Ultrasonic drying | Page 14

Pre-treatment conditions:	25°C for 10min
Dipping emulsion:	2% oil in tap water
Ultrasound (US) conditions:	40 kHz @ 460 W
Drying conditions:	T=60°C; Rh=15%; V=2.5m/s
Prune variety:	GF698
Harvest season:	2014
Sample size:	2.6kg fresh/drying run (~15 times)

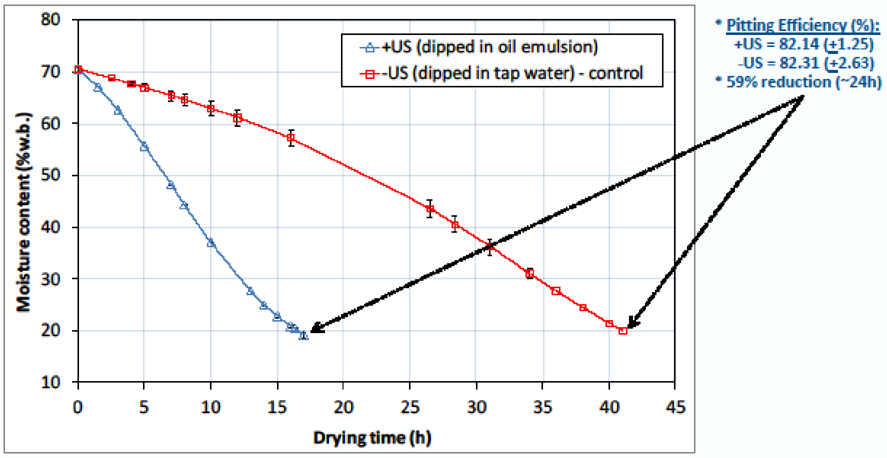


Fig.5. Effect of ultrasound/dipping emulsion pre-treatment for larger sample size (2.6kg) dried at 60°C air temperature (used for pitting trials as well).

Summary:

- Pre-treatments with ultrasound in oil emulsion were found to significantly reduce the drying time with better retention of functional/nutritional properties, depending on pre-treatment conditions.
- The drying conditions (i.e. especially temperature) significantly influenced the magnitude of the effect of pre-treatments – indicating the need to establish the optimum drying conditions (temperature, airflow, humidity).
- The application of ultrasound in oil emulsion pre-treatment did not significantly affect the pitting efficiency of the dried/rehydrated products.
- Experiments undertaken with larger sample size demonstrated the scalability of the process.
- Further experiments are envisaged to be carried out:
  - To assess the effect of pre-treatment conditions (i.e. time, oil concentration, temperature, oil type, ultrasound frequency & power levels, etc).
  - To evaluate the effect of pre-treatment on various drying conditions (temperature, airflow, humidity), and simulated tunnel drying (i.e. parallel & counter flow) drying conditions.

Thank you

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Appendix 3. Media articles.

A3.1. Article published in the Vine Magazine.

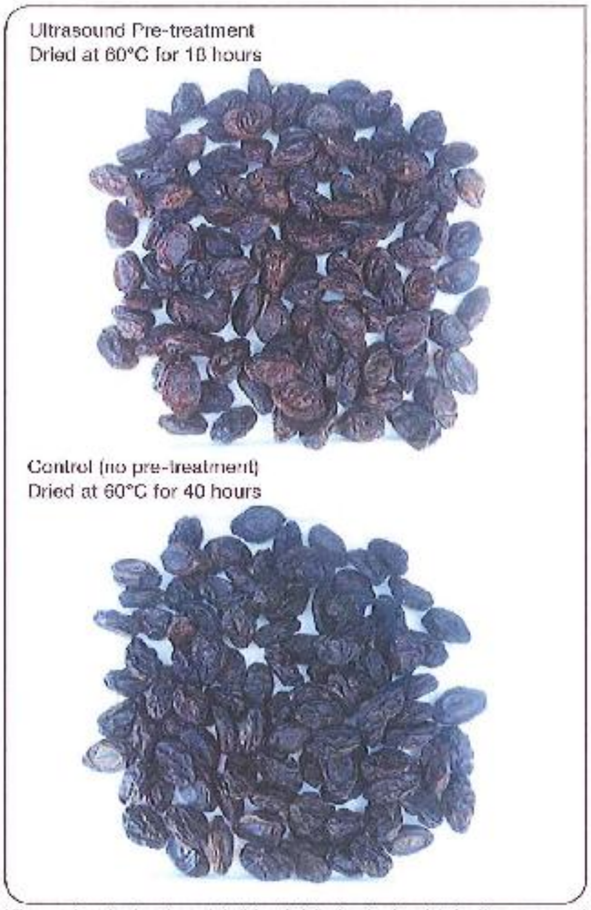
Ultrasound technology helping to improve prune drying efficiency

By Dr Henry Sabarez

A study to develop and optimise the application of ultrasound technology for efficient and sustainable drying of prunes is showing promising results.

A laboratory ultrasonic system was developed to treat fruit samples in an aqueous solution prior to the fruit being dried. The system was evaluated by conducting a series of experiments using 2013 and 2014 fresh plum samples obtained from the industry collaborators in Cobram (Victoria) and Darlington Point (NSW). Fruit was subject to various sonication times, temperatures and ultrasonic conditions (i.e. ultrasonic frequencies and power levels) before being dried.

Results from the preliminary laboratory drying experiments undertaken for the 2013 fruit harvest season have shown the ultrasonic pre-treatment to have significant effect in terms of enhancing the drying process with better retention of the nutritional and functional properties of the product.



Ultrasound pre-treatment results in lighter fruit (top) and reduced drying times compared to untreated fruit that is dried (bottom)

In particular, the results reveal that the ultrasonic pre-treatment in oil emulsion significantly reduced the overall drying time by up to 46% compared to those samples dried without pre-treatment, depending on the ultrasonic pre-treatment and drying conditions.

Ultrasonic pre-treatment also led to lighter coloured dried fruit with significantly higher antioxidant capacity (measured by the Oxygen Radical absorbing Capacity or ORAC assay) and vitamin C retention compared with the non pre-treated samples. Furthermore, the antioxidant capacity levels of the dried plum samples were found to be significantly higher (up to 56%) than the fresh plum samples. These results suggest that the drying process may enhance the bio-availability of the health-promoting components in the fruit with the magnitude of influence depends on the pre-treatment and drying conditions.

Another suite of laboratory drying experiments was conducted for the 2014 fruit harvest season to investigate the effect of ultrasound pre-treatment on the drying process and product quality attributes under different drying conditions.

The results from these drying trials reveal that the effect of ultrasonic pre-treatment varies significantly with the subsequent drying conditions.

The ability of the combined ultrasonic and oil emulsion pre-treatment to improve the efficiency of the drying process appears to be maximised when using a lower drying temperature and that the effect of pre-treatment progressively decreases as the drying temperature increases. For example, drying at 60°C resulted in 57% reduction in the overall drying time with the application of pre-treatment while drying at 70°C and 80°C with the pre-treated samples resulted in 28% and 13% reduction in the overall drying time, respectively.

This indicates that with the application of pre-treatment, drying of prunes can be carried out at lower drying temperature while still achieving faster drying rates (i.e. resulting in increased throughput and reduced energy consumption with better quality of the product).

Further experiments are planned for the 2015 harvest to test the effect of other drying conditions such as relative humidity and airflow and ultrasonic parameters.

Large scale trial

A number of drying trials was carried out with fruit from the 2014 harvest to demonstrate the scalability of the pre-treatment and drying processes, and the impact of such large scale experiments on the rehydrability and pitting of dried prunes at industrial scale conditions, and the corresponding changes in microstructure and antioxidant activity levels.

The large scale experiments were undertaken using about 2.6 kilograms of fresh plums per experimental treatment (~15 times larger than the small scale experiments). Two sets of large scale experiments, including without pre-treatment (control) and with pre-treatment (i.e. using the combined ultrasound and oil emulsion) were carried out and the samples were then subsequently dried at 60°C until the final moisture content reached to the desired level (~20%). The dried samples were sent to Country Foods Pty Ltd (Young, NSW) for rehydration and pitting under commercial conditions.

The results from the large scale experiments showed about 59% reduction in the overall drying time with the application of pre-treatment. This is consistent with the results from the small scale experiments (~150g per experimental treatment), suggesting the scalability of the process. No significant differences in the pitting efficiency between the control and the pre-treated samples were observed. In addition, the pre-treated samples were found to have a lighter colour with higher antioxidant activity level (~60% more) compared with the untreated samples, corroborating with the previous results from the small scale experiments.

The results from the large scale experiments showed about 59% reduction in the overall drying time with the application of pre-treatment... In addition, the pre-treated samples were found to have a lighter colour with higher antioxidant activity level

Microscopy

Untreated and pre-treated partially-dried samples were examined, employing an environmental scanning electron microscopy (ESEM) technique. This detailed view at high magnification shows more disruptions of the waxy skin layer of pre-treated fruit samples compared to the control samples.

In previous studies the waxy skin layer of prunes has been demonstrated to provide a significant barrier to moisture transfer during the drying process. The disruption of the waxy skin layer with the application of pre-treatment is consistent with the observed significant reduction in drying time as a consequence of improved moisture transfer across the waxy skin layer of the fruit.

This project is expected to deliver outcomes that will assist the long term sustainability of the prune industry and maintain its competitiveness through substantial cost savings in the drying process (i.e. increased throughput and reduced energy consumption through low temperature/short drying time) with potential improved returns for a consistent high quality dried product.

DP12001 Ultrasonic drying of horticultural food products *has been facilitated by Horticulture Australia Limited (HAL) in partnership with the Australian Prune Industry Association (APIA). The project has been funded by the national dried prune research and development (R&D) levy with the Australian Government providing matched funding for all HAL's R&D activities.*

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Chilean prune exports up 21% in 2014

Chilean prune exports have grown by 21% this year compared to 2013, reaching 41,000 tonnes, with returns of US$ 200 million.

These figures were reported in a *FreshPlaza News* story (26 November 2014) following a meeting of the Chilean Prunes Association. More than 300 prune producers and exporters attended and were told the sector expects to reach 75,000 tonnes next year, of which 95% is intended for export.

Andrés Rodriguez, Vice President of the association, said that last year the value of these exports reached US$151 million, so "this year we clearly continue to grow in all aspects, confirming Chile's position as the world's largest prune exporter."

According to the report Mr Rodriguez believes that, "The quality and safety of Chilean plums is the main advantage we have to compete overseas; that is an aspect we have to protect and strengthen."

The Australian Bureau of Statics (ABS) collects prune import data for the Australian Prune Industry Association (APIA). Figures to October 2014 showed imported prune tonnages for the 12 months prior was 1,104t well down on the same period last year where 1,447t were imported. Lack of world supply and/or the increase in price per kilogram may be impacting on Australia's imports.

This is significant for the Australian prune industry. With unpredictable weather and several heat waves already felt in spring, it is too early to estimate the Australian level of production for season 2014/2015. If Australia continues to produce lower than average tonnages, processors will have to source fruit from countries like Chile to supply the domestic market. This would mean Australian growers will not be able to take advantage of increasing world prices.

A3.2. Article published in the Prune Industry Advisory Committee Annual Report 2013/14.

Prune

Aus Prunes

HAL Horticulture Australia

INDUSTRY ADVISORY COMMITTEE ANNUAL REPORT 2013/14

Overview

The 2013/14 year witnessed a steady return to average crop levels and levy receipts as a result of normal growing conditions.

The 2013 harvest provided nearly 2,800 tonnes of high-quality prunes of good size and maturity. The majority of Australian production is derived from the Griffith region of NSW. In addition, there are a small number of growers scattered throughout Young, NSW, and Cobram, Victoria. Growers supply fresh or dehydrated product to processors, with prices dependent on gradable sized fruit.

A small number of plantings still exist in the Riverland, South Australia, and some fresh product is sourced by processors from Victoria's Shepparton and Swan Hill districts.

In 2013, the total world production of prunes dropped to less than 200,000 tonnes, about 50,000 tonnes below average. Poor weather, particularly in the Americas, had a major impact on production.

Widespread hail damage and an unusually low crop set impacted the Californian crop, which dropped to about 82,000 tonnes. The five-year average production in California is 130,000 tonnes per year. The crop in Chile was down about 35 percent due to the weather impacts including high temperatures around blossom time. Argentina had similar issues with hail also a major problem. The French crop was of high quality and size, but was down in tonnage. Australia, Italy and South Africa had reasonable crops, although they are relatively small producers in global terms.

When carryover stocks were factored in, the total available prune stocks were about 300,000 tonnes. This quantity is less than the annual long-term world consumption of prunes. Global supplies of prunes were expected to remain below demand for at least the next twelve months and possibly longer. This situation has already caused substantial increases in the cost of prunes imported from Chile and California.

Levy investment

In 2013/14, the total income received was $74,823 of which the Australian Government provided $35,597 of matched funding to support twelve projects in the research and development (R&D) program.

The current levy/export charge is $13.00 per tonne. A total of $51,262 was invested into R&D projects.

In addition to levy funds, $160,142 of voluntary contributions (VC) was invested in supplementing levy-funded projects and solely funding VC-only projects. VC funds were matched by the Australian Government for all R&D activity.

Horticulture Australia Limited (HAL) is responsible for managing these funds and takes advice on how to invest the funds from the Prune Industry Advisory Committee (IAC). Consultation with the IAC is essential in determining the most critical investment priority for the industry, which is to enhance the prune industry's capability and capacity via domestic market and consumer research.

In 2013/14, the Australian Prune Industry Association acted as the service provider on four projects.

The industry also contributes 2.25 percent of levy and/or voluntary contributions (matched to 4.5 percent) to an across industry program that addresses issues that affect all of horticulture, such as water availability, climate change, biosecurity and market access.

Strategic objectives

The process for determining the industry's priorities begins with the development of the industry's Strategic Investment Plan (SIP), which guides future R&D investment over a five-year period. The prune industry priorities for 2013/14 were defined by the current *Prune Industry Strategic Investment Plan 2013–2016*, which can be found at www.horticulture.com.au/industries/prune.

The SIP was developed to reflect the industry's priorities, the Australian Government's rural R&D priorities and is reviewed regularly. The industry's objectives, as outlined in the new strategic plan are:

1. Improve supply efficiency and sustainability (costs/risks)
2. Improve product value (quality and price)
3. Develop new marketing opportunities (demand/sales volume)
4. Improve the rate of adoption of existing technology and provide an enabling environment
5. Efficiently administer the organisation.

R&D program

In 2013/14, the industry undertook four levy-funded projects, five levy and VC-funded projects and three VC-only projects. The strategic thrust of the current R&D program was the ongoing evaluation of imported varieties against the industry standard, D'Agen.

The 2013 International Prune Association (IPA) Congress was hosted in Australia, with different events held in Canberra and Griffith, NSW. Delegates reported that the Conference had exceeded expectations with the high quality of presentations and the keen interest shown by delegates.

A range of high calibre of speakers focused on various topics including the potential of prunes as a 'superfood'.

The projects in this report have been funded by HAL using the prune industry levy and/or voluntary contributions from industry with matched funding from the Australian Government for all R&D activity.

Ultrasonic drying of horticultural food products

A three-year study is aiming to develop and optimise the application of ultrasound technology for efficient and sustainable drying of prunes.

An ultrasonic system was successfully developed to allow for the treatment of fruit samples (prior to drying) in an aqueous solution at various sonication times, temperatures and ultrasonic conditions (ultrasonic frequencies and power levels). The system was evaluated by conducting a series of drying experiments using 2013 and 2014 fresh plum samples obtained from the industry collaborators in Cobram (Victoria) and Darlington Point (New South Wales).

The application of ultrasound was found to provide a significant effect in terms of enhancing the drying process with better retention of the nutritional and functional properties of the product. In particular, the results from the drying tests reveal that the ultrasonic pre-treatment in an aqueous dipping solution significantly reduced the overall drying time of up to 54 percent in comparison with those samples dried without pre-treatment, depending on the ultrasonic pre-treatment and drying conditions.

The antioxidant capacity (measured by the oxygen radical absorbing capacity or ORAC assay) and vitamin C retention were significantly higher with lighter colour for the dried samples ultrasonically pre-treated compared with the non pre-treated samples. Also, the antioxidant capacity levels of the dried plum samples were found to be significantly higher (up to 56 percent) compared with the fresh plum samples. These suggest that the drying process may enhance the bio-availability of the health-promoting components in the fruit with the magnitude of influence depending on the pre-treatment and drying conditions.

The results of the preliminary proof of concept drying trials undertaken during the 2013 fruit harvest season were provided in June 2013. Further drying trials into the effects of ultrasound technology on the drying process and product quality for the 2014 fruit harvest season are expected to be completed by the end of the 2013/14 year. The results of this activity will be provided in the progress report to be submitted in June 2014.

The project is expected to deliver outcomes that will assist the long-term sustainability and maintain competitiveness through substantial cost savings in the drying process (increased throughput and reduced energy consumption through low temperatures and a short drying time) with potential improved returns for a consistent high-quality dried product.

Project DP12001

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