EFFECTS OF DIFFERENT PRE-TREATMENTS ON ENERGY CONSUMPTION DURING FREEZE DRYING OF PINEAPPLE PIECES

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SUMMARY

Osmotic dehydration and microwave heating were combined with freeze-drying to obtain dehydrated pineapple. The effects of combined technologies on energy consumption, drying time and kinetics were analyzed. It was generally observed that the processes that include osmotic dehydration reduced the sublimation kinetics, but showed low consumption of energy during the whole dehydration process. A positive synergistic effect on mass transfer is observed when microwaves are additionally applied before osmotic dehydration and freeze-drying, due to solid gain after osmotic pretreatments; energy utilization throughout the complete dehydration processes can be reduced up to 61.3% when measured as kJ/kg of obtained product.

Introduction

The main reason to dehydrate fruits is to extend their shelf life beyond that of the fresh material without the need for refrigeration. Known as the oldest method of food preservation, dehydration preserves fruits because it reduces the water content to levels at which growth and development of microorganisms is inhibited. Additionally, enzyme activity and chemical changes are decreased. On the other hand, changes that affect the quality of food such as shrinkage, color and flavor variations, and reduction of nutritional value may also occur during drying. Thus, the study of dehydration and its effects on fruit quality is a relevant topic.

There are many ways of taking the water away from biological materials: air drying, direct contact, vacuum, etc. However, products obtained from freeze drying, which is based on dehydration by sublimation of frozen water, are recognized for their quality and rehydration capacity. Therefore, it is common to find references where freeze drying (FD) is the benchmark method for water removal (Beaudry *et al*., 2004; Marques *et al*., 2009; Michalczyk *et al*., 2009). However, FD is also known for its slow drying rates, high operation cost and low energy efficiency in comparison with other ordinary drying technologies (Huang *et al*., 2009). Because of these drawbacks, FD has been mainly applied to dehydrate high value products such as pharmaceuticals, microorganisms and some aromatic beverages like coffee (Pardo, 2002; Chen and Wang, 2007; Meng *et al*., 2008).

Studies to reduce FD cost have been carried out during the past three decades. Some of these studies have focused on abolishing the cost of generating high vacuum and therefore concentrated efforts on developing equipment for atmospheric FD (Wolf, 1990; Claussen *et al*., 2007; Rahman and Mujumdar, 2008). Others have tried several combinations of treatments to reduce energy use during FD (Xu *et al*., 2006; Reyes *et al*., 2008; Huang *et al*., 2009), and others have tried to reduce FD time by enhancing heat transfer (Zhang *et al*., 2006; Duan *et al*., 2007; Wang *et al*., 2009). Finally, there are plenty of studies to replace FD by reproducing its effects on the product. The latter is the case of combined treatments such as osmo-convective drying and microwave assisted air drying, which have been shown to have good effects on color, rehydration ratio and nutrient retention of fruits, comparable to those of FD fruits (Prothon *et al*., 2001; Beaudry *et al*., 2004; Zhang *et al*., 2006; Andres *et al*., 2007).

The use of microwaves (MW) to assist the drying processes has been widely studied (Zhang *et al*. 2006; Orsat *et al*., 2007) and several advantages have been reported: shorter drying times, improved product quality and heat transfer rates. However, existing applications are limited due to high start-up costs and relatively complex technology when compared to conventional drying methods (Schubert, 2006). As microwaves can penetrate tissue samples, their center can easily reach temperatures near water's boiling point; therefore, during MW drying mass transfer is influenced by a pressure gradient, which is the main driving force. A too rapid mass transport may cause quality damage or undesirable changes in the food texture by 'puffing' (Nijhuis *et al*., 1998). However, this may or may not be a limitation, depending on the desired quality attributes of the final product. For example, the rapid evaporation caused by MW could yield cell wall damage that could increase mass

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EFFECTOS DE DIFERENTES PRETRATAMIENTOS SOBRE EL CONSUMO DE ENERGÍA DURANTE LA LIOFILIZACIÓN DE TROZOS DE PIÑA

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RESUMEN

A fin de obtener piña deshidratada fueron combinados tratamientos de deshidratación osmótica y calentamiento por microondas con liofilización. Se analizaron los efectos de las tecnologías combinadas sobre el consumo de energía, tiempo de secado y parámetros cinéticos. En general, se observó que los procesos que incluyen deshidratación osmótica redujeron la cinética de sublimación, y mostraron un bajo consumo de energía durante todo el proceso. Un efecto sinérgico positivo sobre la transferencia de masa se observó cuando las microondas fueron adicionalmente aplicadas antes de la deshidratación osmótica y la liofilización, debido a la ganancia de sólidos tras los pretratamientos osmóticos; la utilización de energía a lo largo de todo el proceso de deshidratación puede ser reducida hasta en 61,3% cuando se mide en kJ/kg de producto obtenido.

EFEITOS DE DIFERENTES PRETRATAMENTOS SOBRE O CONSUMO DE ENERGIA DURANTE A LIOFILIZAÇÃO DE PEDAÇOS DE ABACAXI

José Mauricio Pardo e Dolly Andrea Leiva

RESUMO

Com o fim de obter abacaxi desidratado foram combinados tratamentos de desidratação osmótica e aquecimento por microondas com liofilização. Analisaram-se os efeitos das tecnologias combinadas sobre o consumo de energia, tempo de secado e parâmetros cinéticos. Em geral, se observou que os processos que incluem desidratação osmótica reduziram a cinética de sublimação, e mostraram um baixo consumo de energia durante todo o processo. Um efeito sinérgico positivo sobre a transferência de massa se observou quando as microondas foram adicionalmente aplicadas antes da desidratação osmótica e a liofilização, devido o ganho de sólidos depois dos pretratamentos osmóticos; a utilização de energia ao longo de todo o processo de desidratação pode ser reduzida até em 61,3% quando se mede em kJ/kg de produto obtido.

transfer when combined with other drying methods, such as air drying or osmotic dehydration but, on the other hand, it can induce sample shrinkage and nutrient loss (Zhang *et al*., 2006).

Osmotic dehydration (OD) is well known as a drying pretreatment for food materials because it can reduce energy costs and also improve quality of the final products (Andres *et al*., 2007; Ortega-Rivas, 2007; Lombard *et al*., 2008). OD is usually carried out by immersion of the samples in a highly concentrated solution of sugar or salt. It has been applied successfully to a variety of fruits by reducing up to 30% of their initial moisture content (Rastogi *et al*., 2002; Beaudry *et al*., 2004). The chemical potential that exists between solution and food sample leads to mass transfer fluxes, in which water flows out of the sample and solutes enter into the tissue. However, since osmotic pressure is the unique driving force for mass transfer, OD is a slow process. Other processes, such as vacuum infusion, ultrasound, high pressure, high-intensity electric field pulses, microwaves, blanching and freezing have been investigated earlier in order to improve diffusion coefficients during OD (Rastogi *et al*., 2002; Taiwo *et al*., 2003; Deng and Zhao, 2008; Dhingra *et al*., 2008; Pardo and Leiva, 2009).

The selection of the proper drying technology or combination of technologies can affect final product quality and drying cost. Therefore, this study focuses on the reduction of energy use during freeze drying of pineapple slices. Pretreatments such as OD, MW and their combinations are studied to see their effect on water content, sublimation time and overall energy consumption during pineapple freeze drying.

Materials and Methods

Pineapples (Var. Golden) were peeled and cut into triangular pieces (10mm base × 30mm sides × 5mm width).

Osmotic dehydration was carried out in concentrated sucrose solutions (60°Brix). Recipients were filled with the osmotic solution at 20°C and 50g of pineapple pieces, maintaining a product solution ratio of 1:5 w/w. Osmotic solution was not agitated during the experimental procedures. After withdrawing the pineapple pieces from the osmotic solution they were placed on an absorbent cloth to remove excess of solution on the surface.

Microwave heating was carried out using a microwave oven (HACEB HM1.1). Samples of 50g of pineapple pieces were heated using a power of 20 kW/kg.

Freeze drying was carried out using a Labconco tray freeze dryer (4.5l benchtop) under an absolute pressure of 0.15mbar. Samples were heated unidirectionally using radiation heat transfer from the upper tray; the heating tray temperature was maintained at 40°C from the first processing hour up to 8h. The weight of the samples was followed by placing an electronic Mettler balance (±0.01g) inside the drying chamber. Weight recordings were made every 30min during the first 8h.

All combined treatments used in this work were carried out three times and the procedures used are summarized in Table I. Additionally, Figure 1 summarizes the en-

TABLE I
SUMMARY OF TREATMENT COMBINATIONS USED IN THIS WORK

Code	Treatment description
ODFD	OD during 75min and FD during 24h
MWFD	MW during 1min and FD during 24h
MWODFD	MW during 1min, OD during 74min and FD during 24h

ergy consumption points during different drying treatments, and Table II explains the calculation method for energy used in every consumption point. Energy calculations have been done using the definition of good energy or valid energy (GE; Huang *et al*., 2009), which excludes all energy that is not used in the operation (heat losses, equipment inefficiencies etc).

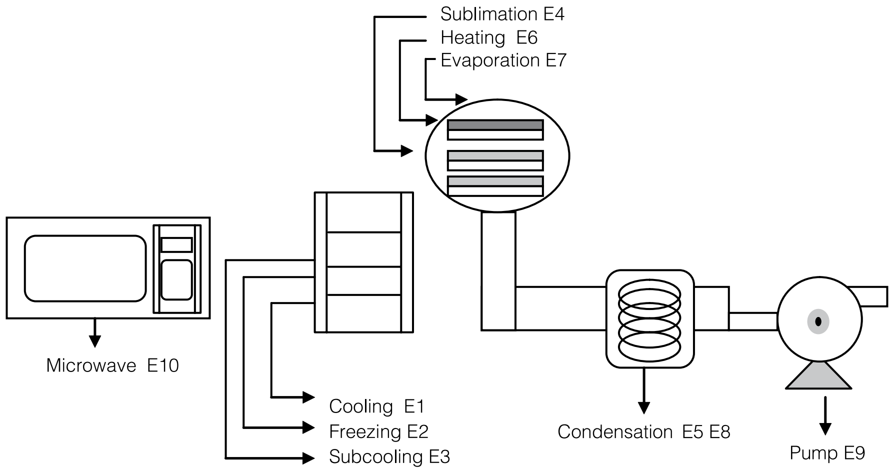

Figure 1. Different points in which there is significant energy consumption during the drying procedure.

Results and Discussion

In Table III it can be appreciated that the combined treatment MWOD is the one that favors most mass transfer in both directions (solid gain and water loss), a result that is consistent with earlier findings (Pardo and Leiva, 2009). Differences between MWOD and OD are explained on the basis of the puffing phenomena that occurs during the MW treatment, which fractures cell walls and therefore opens new paths for mass to be transferred faster during osmotic dehydration (Zhang *et al*., 2006). Additionally, it is seen from Table III that MWOD uses 45.5% of the energy needed by MW to extract 1kg of water. These results show the positive influence of osmotic treatments on the reduction of energy use at least on the first drying step. Finally, the amount of energy used in MWOD to extract 1kg of water is equivalent to that used by an efficient convection dryer (Alves and Roos, 2006). Although this is a good level, it was expected to observe a lower value due to efficient energy transmission attributed to microwave heating processes (Bradshaw, 2006; Zhang *et al*., 2006).

A linear trend was observed in freeze drying curves (water loss through time between 1 and 7h), which is typical under the experimental conditions used in this work (Sagara, 2001; Pardo, 2002); in fact, all correlation coefficients obtained from these regressions were >0.90. Thus, a simple model, based on initial moisture contents and experimental drying kinetics slopes, can be built in order to estimate drying times under different conditions. Predicted times for the different settings used in this work are summarized in Figure 2. Note that even though freeze drying is composed of two drying stages, sublimation of frozen water and desorption of unfrozen water (Ratti, 2001), the authors consider that the time spent during the desorption stage can be neglected without affecting the main objectives of this work. Therefore, the estimated sublimation time, assumed to represent the total drying time, is given by

$$t_s = \frac{H_{bf} - H_{bi}}{m_s}$$

where, t_s: total sublimation time, H_{bf} and H_{bi}: final and initial moisture content, and m_s: slope obtained from empirical drying curves. Two statistically different groups were identified (95% confidence) from the drying kinetics perspective (x-axis in Figure 2). Group A is conformed by samples processed under FD and MWFD, and group B is con-

TABLE II
SUMMARY OF EQUATIONS USED TO CALCULATE ENERGY CONSUMPTION AT DIFFERENT POINTS OF THE DRYING PROCESS

Name And Description	Equation	Symbols
E1 Sensible heat during cooling sample (above freezing)	mCpΔT	m: total fruit mass (kg) Cp: specific heat of fruit (kJ/kg°C) ΔT: T1-T2 T1: ambient temperature (°C) T2: freezing temperature of fruit (°C)
E2 Latent heat during freezing	mλ	m: freezable water mass of the fruit (kg) λ: latent heat of freezing water (kJ/kg)
E3 Sensible heat during cooling sample (below freezing)	mCpΔT	m: total fruit mass (kg) Cp: specific heat of fruit (kJ/kg°C) ΔT: T2-T3 T3: subcooling temperature (°C)
E4 Sublimation heat	mλ	m: freezable water mass of the fruit (kg) λ: latent heat of sublimation (kJ/kg)
E5 Latent heat of Condensation (vapour-solid)	mλ	m: freezable water mass of the fruit (kg) λ: latent heat of condensation (kJ/kg)
E6 Sensible heat during heating of dried sample	mCpΔT	m: semi-dry fruit mass (kg) Cp: specific heat of fruit (kJ/kg°C) ΔT: T4-T3 T4: heating temperature (°C)
E7 Latent heat of vaporisation of non frozen water	mλ	m: steam mass (kg) λ: latent heat of vaporization (kJ/kg)
E8 Latent heat of condensation of evaporated water (vapor-solid)	mλ	m: vapour mass (kg) λ: latent heat of condensation (kJ/kg)
E9 Consumption of vacuum pump	(P-Pfc)Vt(tp+ts)/tfv	P: atmospheric pressure (Pa) Pfc: chamber pressure during FD (Pa) Vt: total volume of air in freeze dryer (m^3) tp: time for primary drying stage (h) ts: time for secondary drying stage (h) tfv: working time for vacuum pump from atmospheric pressure to 100Pa (h)
E10 Consumption microwave	Pt	P: microwave Power (kJ/s) t: time (s)

formed by MWODFD and ODFD related samples. From these results, it is remarkable that those samples processed using osmotic dehydration showed the smallest slope values, indicating that freeze drying rates tend to be slower after these kinds of treatments. This is in accordance with previous studies on combined drying procedures (Prothon *et al*., 2001; Andres *et al*., 2007), which attributed the results to the fact that sucrose molecules in the pretreated tissue increase the internal resistance to mass transfer, and to a crust formed by the osmotic agent on the surface of the sample. Additionally, it is interesting to see that there is no effect of MW on sublimation kinetics (MWFD) when compared with blank procedure (FD). The opposite trend was observed during MWOD pretreatment (Table III), after which an increased mass transfer was observed due to cell rupture. It seems that the MW puffing effect is covered up by the crystal formation that occurs during freezing of the sample prior to the sublimation stage, which can cause cell rupture as well (Marques *et al*., 2009).

TABLE III
MASS TRANSFERRED AND ENERGY USED DURING DIFFERENT PRETREATMENTS

Pretreatment	ΔMw	ΔMs	Energy	Water content after pretreatment
	%	%	kWh/kg water	%w.b.
OD	16.3 ±0.7	3.6 ±0.7	0.0	75 ±0.8
MW	15.0 ±2.3	0	2.2	79 ±2.8
MWOD	33.5 ±0.8	14.6 ±0.3	1.0	60 ±1.6

TABLE IV
ENERGY CONSUMPTION OVER ALL DRYING PROCEDURE*

Energy Consumption Point	FD	ODFD	MWFD	MWODFD
	(kJ/kg of removed water)			
Sensible heat during cooling (E1)	98.9	86.4	84.7	84.2
Latent heat during freezing (E2)	333.6	257.5	264.4	188.8
Sensible heat of cooling (E3)	165.9	138.0	134.7	116.0
Sublimation heat (E4)	2818.5	2175.4	2233.6	1594.6
Latent heat of Condensation (E5)	2818.5	2175.4	2233.6	1594.6
Sensible heat during heating (E6)	37.8	52.9	43.6	80.4
Latent heat of vaporisation of non frozen water (E7)	9.2	12.3	11.8	23.5
Latent heat of condensation of evaporated water (E8)	11.5	15.5	14.9	29.6
Consumption of vacuum pump (E9)	173.2	188.1	123.2	109.8
Consumption of microwave (E10)	0.0	0.0	1431.4	1439.4
Total energy	6467.1	5101.4	6575.9	5261.0
	(kJ/kg obtained product)			
*Total energy	33721.0	18961.5	34258.8	13047.6

* It is important to note that in this line measurement units change.

From the drying time perspective (y-axis Figure 2), two statistically different groups were identified: group 1, composed by samples processed under FD and ODFD and group 2, made up by samples dried under MWODFD and MWFD. These results show that samples processed using microwaves tend to dry in a shorter time. Furthermore, samples processed using MW and OM are freeze-dried using 38.7% less time than fresh fruits (FD); even if the pretreatment time (75min) is added, MWODFD uses 26% less time to dry than FD. Thus, experiments show that MWODFD drying conditions are favorable to reduce energy consumption because they extract more than twice the amount of water removed by MWFD at the pretreatment stage, before FD. Therefore, the GE involved in phase change (freezing, sublimation, condensation) is reduced.

Table IV and Figure 3 summarize calculations made on GE consumption using the equations in Table II. From these results it is seen that more than 90% of GE is consumed at the phase-changing points: E2 (freezing), E4 (sublimation), E5 (condensation), and, where applicable, E10 (microwaves). On the other hand, a comparison between different drying procedures showed that all combined treatments tend to reduce energy consumption per kg of extracted water, except for MWFD. This shows that under the experimental conditions employed, MW as pretreatment to FD is not attractive from the environmental and

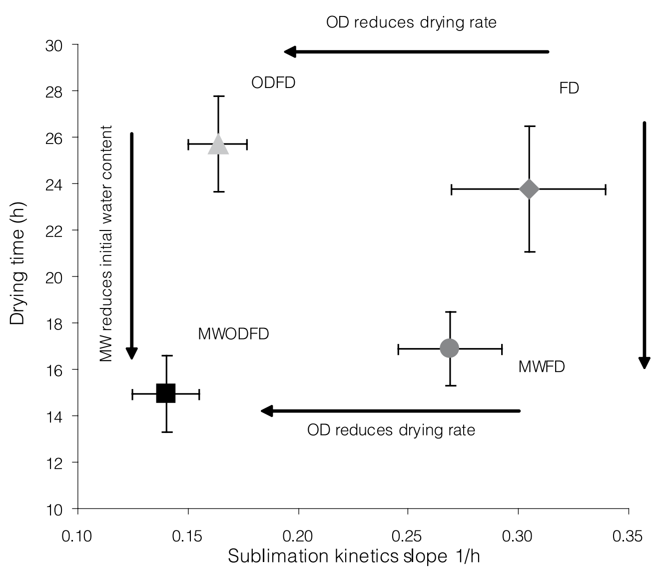

Figure 2. Drying time and sublimation kinetics of the different treatments. OD: osmotic dehydration, FD: free drying, MW: microwave.

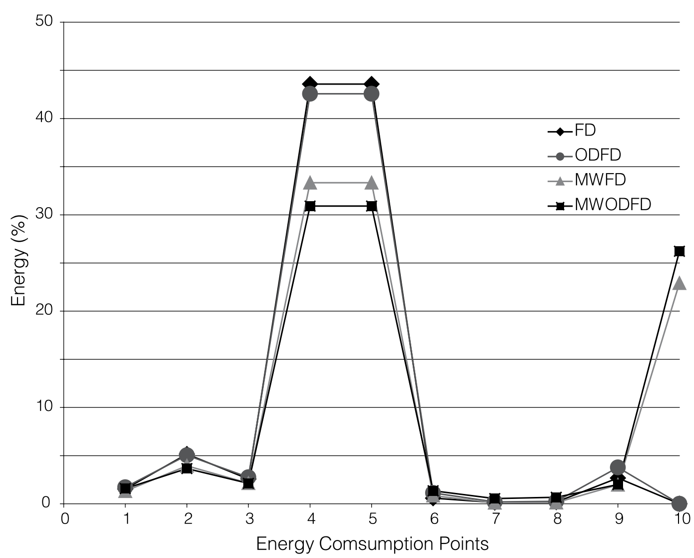

Figure 3. Energy consumption (%) during the different drying treatments.

monetary point of view. Additionally, it can be seen that when an osmotic treatment is involved, energy savings tend to be ~20% (21.1% for ODFD, 18.6% for MWODFD). These results are explained by the fact that osmotic dehydration does not need a water phase change in order to separate water from the sample, which is the main advantage of this process (Dhingra *et al*., 2008).

Finally, it should be highlighted that osmotic dehydration implies not only movement of water out of the sample, but also movement of solids in the opposite direction; therefore, the yield of processes that include OD as pretreatment is higher than those that don't. These solid gains imply that GE consumed per kg of product is expected to be decreased when osmotic pretreatments are used, as has been observed in this work. The final line of Table IV shows how dried pineapple pieces obtained using osmotic pretreatments (OD, MWOD) tend to consume less GE. The ODFD treatment uses 56.2% of the GE consumed by FD, and MWODFD uses 38.7% of the GE used by FD. These results reveal a synergistic effect when MW is applied before OD, which can generate substantial energy savings in freeze drying plants without investing in new freeze drying equipment, which tends to be more expensive than MW drying equipment. Finally, it is important to note that even though ODFD reduces GE consumption, it is one of the lengthiest treatments, which seems to be unreasonable. However, as equipment inefficiencies (bad energy) are not included in the analysis, the effect of time on energy use tends to be diminished, showing that, before scaling up these results, further studies on the effect of equipment inefficiencies on the cost of the product should be carried out.

Conclusions

A positive synergistic effect on mass transfer is observed when microwaves are applied before osmotic dehydration and freeze drying. Good energy used during the whole dehydration process (measured in kJ/kg of extracted water) could be reduced up to 18.6% using this combination (MWODFD). Furthermore, due to solid gain after OD pretreatment, GE use throughout all the dehydration process is reduced up to 61.3% when measured as kJ/kg of obtained product.

The use of MW and MWOD as pretreatments for freeze drying opens a good opportunity to increase plant capacity without investing in new freeze drying equipment, which tends to be more expensive than microwave drying equipment or the apparatus needed to carry out osmotic dehydration.

Even though GE savings were observed after ODFD, this treatment tends to increase total drying time. Therefore, further cost analysis should include the effect of this treatment on equipment occupation and the effect of equipment inefficiencies ("bad" energy use) on total cost before deciding its implementation on an industrial scale.

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