Study of Iron Yam-Chip (*Dioscorea opposita* Thunb. cv. Tiegun) Dehydration Using Far-Infrared Radiation Assisted Heat Pump Drying

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Abstract Iron Yam chips were dried using a heat pump (HP) dryer alone or in combination with far infrared radiation (FIR) at 500, 1500 and 3000 W (500 FIR, 1500 FIR, and 3000 FIR, respectively). The experimental results were presented in terms of the drying characteristics, and dried product qualities (shrinkage, color, texture, percentage of rehydration, and moisture content). Samples with initial moisture content of approximately 76% (w.b.) were dried to a final moisture content of < 17% (w.b.) at the drying temperature of 50°C and at an air flow rate of 1.0 m s-1 for all of the experiments. The data showed that FIR+HP drying increased the drying rate by reducing the drying time, and the resulted dried Iron Yam chips generally had higher values of lightness and comparable values of redness and yellowness than the HP-treated samples. In the case of HP+1500FIR, the dried Iron Yam chips had lower shrinkage, improved rehydration ability, lower hardness and higher brittleness than those dried by HP, HP+500FIR and HP+3000FIR. It is worth noting that the total energy used for FIR-assisted drying processes decreased with the increase of FIR intensity. The present data suggest that HP+FIR drying is an effective and economical method for Iron Yam chip drying, and HP+1500FIR can obtain the best dried product.

Keywords: heat pump, far-infrared radiation, drying, iron yam chips

Cite This Article: Song Xiaoyong, and Cheng Luming, "Study of Iron Yam-Chip (*Dioscorea opposita* Thunb. cv. Tiegun) Dehydration Using Far-Infrared Radiation Assisted Heat Pump Drying." *Journal of Food and Nutrition Research*, vol. 3, no. 1 (2015): 20-25. doi: 10.12691/jfnr-3-1-4.

1. Introduction

Yam is a popular food consumed in China, and are used as functional foods and herbal medicinal ingredients in traditional Chinese medicine [1,2,3,4]. Iron Yam, specialty in Henan province, is normally consumed in fresh form. However, fresh Iron Yam is difficult to store and easy to deteriorate during storage. In addition, Iron Yam is a climacteric food and it is vulnerable to damage during transportation, preservation and marketing [5]. After being wounded and contaminated, both qualitative and quantitative deteriorations occur through nutrition loss and physiological disorder [6]. So it is desired to develop a stable form dried iron yam products.

Drying is largely utilized to stabilize the product by decreasing its water activity and moisture content, and reducing quality losses [7]. Compared to fresh products which can be only kept for a few days under ambient conditions, dried products can be stored for months or even years without appreciable loss of nutrients [8]. Besides, drying can also create new product-forms, which add value to raw materials.

Iron Yam chips can be produced by various conventional drying methods, and the most common technique is hot air drying which is a simple process. However, due to the low thermal conductivity and internal resistance to moisture transfer of food materials, this method always lead to low efficiency of heat transfer, and the quality of the dried product is generally reduced and often unsatisfactory.

Heat pump (HP) drying can improve energy efficiency and independently control the drying temperature and air humidity [9,10,11,12] which is especially suitable for temperature sensitive vegetables and fruits as drying can occur at low temperature [13,14,15]. However, heat pump drying is a rather slow drying process. In order to reduce the drying time, it is necessary to add an extra source of energy to the system. Far-infrared radiation (FIR) has received much attention recently, which is one possible means for the above purpose [16]. During FIR drying, the energy in the form of electromagnetic wave is absorbed directly by the sample without any loss to the environment leading to considerable energy savings [17]. In addition, infrared radiation technology for dehydrating foods could reduce drying time, maintain uniform temperature in the product, and provide better-quality finished products [18]. This drying method is especially suitable for thin layers of material with large surface exposed to radiation [16]. Some studies have been reported in the literature on the influence of the far infrared radiation combined with low-

pressure superheated steam drying [19,20], freeze drying [21], vacuum drying [22], and convective drying [23,24]. On the drying properties of Iron Yam, there are few articles focusing on the combination of far infrared radiation and heat pump drying. The characteristics of longan [25], squid fillets [26], and banana chips [27] dried using a combination of heat pump drying and far infrared radiation were reported in recent years. To the best of our knowledge, there is little study on the effects of FIR assisted HP drying on the qualities of Iron Yam chips.

To attain the advantages of the above-mentioned drying techniques, the combination of heat pump and far-infrared radiation drying is proposed as a drying technology for Iron Yam chips in this study. The effects of various radiation powers on the drying characteristics of Iron Yam chips as well as the energy consumption of the process were investigated and discussed.

2. Materials and Methods

2.1. Materials Preparation

Fresh Iron Yams (*Dioscorea opposita* Thunb. cv. Tiegun) purchased from a local market in Zhengzhou, China were brought to Food Engineering Laboratory and stored at 4°C. The yams with similar size were selected according to the required cylindrical form. Before each drying experiment, Iron Yams were peeled, and both ends were removed and discarded. Thereafter, the fruits were sliced to 3 mm thickness pieces using a cutting machine immediately, and dipped into 0.005 mol L^{-1} citric acid solution for 10 min. After draining the excess water, the Iron Yam chips were placed on the tray dryer in a single layer.

2.2. Experimental Setup and Methods

The self-made experimental drying apparatus combined heat pump dryer with FIR is shown in Figure 1. The dryer consists of a stainless steel drying chamber with inner dimensions of 30 cm × 60 cm × 50 cm, a 1.5 kW heat pump to supply heat to the drying chamber, and a centrifugal fan driven by 1.0 kW motor. Six infrared heaters (each with a maximum power of 500 W) were installed into the drying chamber, three FIR heaters at the top and three at the bottom of the drying chamber. Two wire mesh trays were placed midway between, and parallel to the top and bottom heaters. The distance between FIR heaters and the trays was fixed at 15 cm. The dryer also includes a 2.0 kW capacity evaporator, a condensing unit, which consists of a 0.6 kW compressor and a 3.0 kW capacity condenser. We assume that the samples experienced the same heat transfer, because the distance between the FIR-heaters and samples were the same and the samples were placed close to one another. The thermal inertia of the IR lamps was assumed to be negligible. All heat pump drying experiments were conducted at 50°C and at the superficial air velocity of 1.0 m s^{-1}. Pretreated samples (ca. 2000 ± 10 g) were spread as a single layer on a mesh tray. Each slab was spaced without touching the adjacent slab, and dried at 50°C (HP), 50°C + 500 W (HP + 500 FIR), 50°C + 1500 W (HP + 1500 FIR), or 50°C + 3000 W (HP + 3000 FIR). The electric energy consumption of the drying processes was measured with the use of a watt-hour meter and a power meter (D9mA-1, Shanghai Diyi Electronic Instrument Co., LTD, Shanghai, China) with an accuracy of ±1%. A sample of about 10 ± 2 g was placed in a thin layer on a small stainless steel net (4 cm × 4 cm) and placed at the center of the same drying tray. At various time intervals, the steel net was taken out of the drying chamber, and moisture loss from the samples was determined by weighing the mass changes of the net using an electronic balance with a precision of ±0.01 g. The final moisture content (w.b.) was estimated as the weight percentage of the mass loss divided by initial water content, obtained through the drying curve. After 30 h treatment, the final moisture content of the sample was <17% (w.b.). The dried Iron Yam chips were allowed to cool down to room temperature for about 10 min and then packed immediately into polyethylene bags for further analysis. All experiments were carried out in triplicate and the average values were reported.
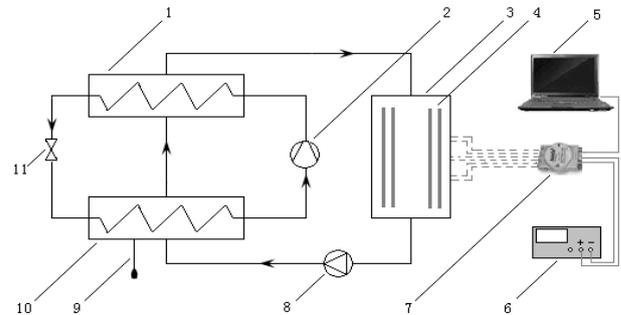

Figure 1. Schematic diagram of experimental setup

1 Condenser 2 Compressor 3 Drying chamber 4 Far infrared heater 5 Computer 6 DC regulated power supply 7 Data logger 8 Fan 9 outlet 10 Evaporator 11 Throttle

2.3. Estimation of Diffusion Coefficients

Fick's laws of diffusion have been frequently adopted in the literature to describe the diffusion of moisture within dried materials [7]. Assuming uniform initial moisture distribution and negligible external resistance, the drying process of Iron Yam chips conforms to Fick's second law. The effective water diffusion coefficient was computed by Eq. (1) [27]:

$$MR = \frac{M_t}{M_0} = \frac{8}{\pi^2} \exp\left(-\pi^2 \frac{Dt}{4L^2}\right) \qquad (1)$$

where *MR* is the moisture ratio, a dimensionless quantity; *D* is the effective diffusion coefficient (m^2 s^{-1}); *t* is the drying time (min) ; M_t is the moisture content at *t* time, (%, w.b.); M_0 is the initial moisture content, (%, w.b) and *L* is the half-thickness of the chip (m).

2.4. Moisture Content Measurement

At the end of each experiment, the moisture content was obtained by drying the samples to constant mass in a vacuum oven (DZF-6050, Shanghai LinPin instruments co., LTD, Shanghai, China) at 70°C, followed by the AOAC standard procedure [28]. The sample mass was determined using a digital balance (PL2002, Mettler Toledo, Switzerland).

2.5. Texture Measurement

Texture properties of the dried samples were evaluated using texture analyzer model TA-XT plus (Stable Micro Systems Ltd., Surrey, England, U.K.) in compressive form. The Iron Yam chips were fractured with a 2-mm cylindrical probe at a test speed of 1 mm s^{-1}. The probe (flat end) moved down vertically and crossed over the sample slice placed on the test board. The hardness is defined as the maximum force in the force–deformation curve while the brittleness is determined by the number of peaks [29]. Twenty measurements were performed for each sample obtained from different drying condition.

2.6. Shrinkage

Shrinkage is usually expressed as the ratio between the volume of the sample after and before drying. The liquid displacement method was applied to evaluate drying shrinkage [27]. Measurements were made as quickly as possible (less than 30 s) to avoid water uptake by the samples. Shrinkage is expressed as percentage of the sample volume change compared with the original volume.

$$Shrinkage = \frac{V_0 - V_f}{V_0} \times 100\% \qquad (2)$$

where V_0 is the initial volume of the sample before drying (cm^3) and V_f is the volume of the sample after drying (cm^3). The average percentage shrinkage of the samples was reported. All measurements were done in triplicate.

2.7. Rehydration Ratio

Rehydration experiments were performed according to the method described by Deng et al [26]. Dried Iron Yam chips were immersed in distilled water at 50 ± 1°C, taken out after 30 min, and drained on a mesh for 60 s to eliminate the superficial water. The changes of sample weight were recorded. Rehydration rate (Rr) is defined as the ratio of the weight of the rehydrated sample to the dry weight of the sample.

$$Rr = \frac{M_f}{M_0} \qquad (3)$$

Where M_f is the sample weight after absorbing water, and M_0 is the sample weight of dried material. All rehydration experiments were carried out in triplicate.

2.8. Differences in Color

The color of the dried samples was measured using a Color Difference Meter, following the method described by Song and Li [30] with some modifications. CIE-Lab coordinates were obtained from the reflection spectra of the samples by a D65 illuminant and observer angle 10°. Color parameters ranged from black (L^* =0) to white (L^* =100); greenness (-a^*) to redness (+a^*); and blueness ($-b^*$) to yellowness (+b^*). Total color differences (ΔE^*) were calculated based on the following equation:

$$\Delta E^* = \left[(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2 \right]^{0.5} \qquad (4)$$

Where $\Delta L^* = L^* - L_0^*$, $\Delta a^* = a^* - a_0^*$, $\Delta b^* = b^* - b_0^*$. L^*, a^*, and b^* are the measured values of dried samples, and L_0^*, a_0^*, and b_0^* are the values of original Iron Yam chips.

Because the colors of the dried Iron Yam chips were not uniform throughout their surface, the samples were ground to power using a small-scale blender before each color measurement. One gram of Iron Yam powder was put into a 2-cm diameter aluminum vessel. The lens of the colorimeter was directly placed on aluminum vessel to measure the color values. Twenty individual samples were tested for each treatment.

2.9. Energy Efficiency

The energy efficiency of the drying processes was indicated in terms of the specific energy consumption, which was calculated as follows [27]:

$$SEC = \frac{E}{m} \qquad (5)$$

Where *SEC* is the specific energy consumption (k W h kg^{-1} water), *E* is the measured electric energy consumption of the HP or HP+FIR (k Wh) and *m* is the amount of water removed from Iron Yam chips (kg), which could be estimated as the difference between the initial and final mass of the products.

2.10. Data Analysis

Statistical analysis of variance (ANOVA) was done using SAS (SAS Inst., Inc., Cary, N.C., USA). The significance of differences between means was determined by least significant difference (LSD) test at P<0.05.

3. Results and Discussion
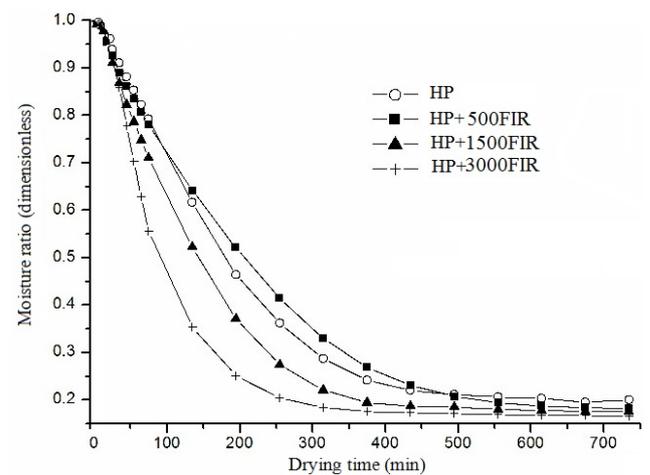
3.1. Drying Characteristic Curves

Figure 2. Drying curves of Iron yam chips as a function of drying time by heat pump (HP) drying alone or combined with far infrared radiation (FIR) at 500, 1500 or 3000 W.

Figure 2 shows the drying curves for the different treatments. These curves revealed that the decrease of moisture content versus time was in a non-linear fashion, which had the similar shape with the dehydration curves performed by Borompichaichartkul et al [31]. indicating

that the moisture movement was controlled by diffusion and the diffusion was dependent on the moisture content of the samples. The removal of moisture from the product at lower moisture content became increasingly difficult. In addition, in the later stage of drying, the HP + FIR methods had a stronger dehumidification capacity compared with the single heat pump drying. For example, 500 min after the drying system began, the moisture content of the Iron Yam slices dried from the single heat pump still maintained relatively high levels. FIR could be directly absorbed by Iron Yam chips, increasing the sample temperature faster than that of Iron Yam chips dried by HP only. As a result, the moisture in the Iron Yam chips dried by the combination of HP + FIR evaporated more rapidly.

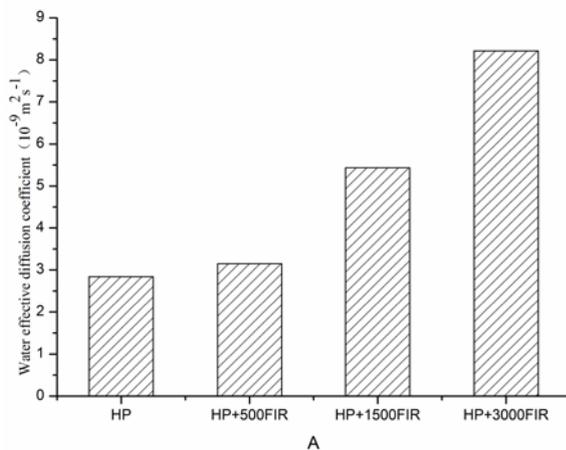## 3.2. Effective Water Diffusion Coefficient

Figure 3. Effective water diffusion coefficients of Iron yam chips as a function of drying time by heat pump (HP) drying alone or combined with far infrared radiation (FIR) at 500, 1500 or 3000 W

Internal moisture diffusion coefficient reflects the dehydrated ability of material in a certain drying conditions, and is one of the most important parameters to optimize the drying process [27]. The effective water diffusion coefficients for the different treatments were calculated using Fick's law and shown in Figure 3. The moisture diffusion coefficient increased when FIR was added. The moisture diffusion coefficient of HP + 1500 FIR and HP + 3000 FIR increased up to 1.9 and 2.9 times than that of the control (HP). The far-infrared radiation auxiliary heat pump drying effectively improved the drying efficiency of Iron Yam chips.

3.3. Moisture Content

At the end of the drying process, the moisture content data of Iron Yam slices by different treatments are shown in Table 1. We can see that the moisture content of Iron Yam chips dried by HP + FIR was lower than that of samples dried by HP treatment only, and decreased with increasing far infrared heating power. There were significant differences between HP+1500FIR and HP treatments (P<0.05), HP+3000FIR and HP treatments (P<0.05), however, no significant differences were found between HP+500FIR and HP treatments (P>0.05).

3.4. Shrinkage and Rehydration

Different drying treatments did not affect the shrinkage of Iron Yam chips, however, rehydration was significantly affected by the treatments (Table 1). The highest value of rehydration of Iron Yam chips was recorded in the treatment with HP +1500FIR. In this treatment, more pore-structures may have been formed due to the more intense moisture diffusion inside the Iron Yam chips. In contrast, the rehydration of Iron Yam chips was lowest in HP+3000FIR. The reason may be that higher radiation power (3000W) resulted in so fast shrinkage of the Iron Yam texture, thereafter organization-gaps in them decreased, the fibers shortened, water-holding capacity and rehydration capacity declined.

Table 1. Properties of Iron yam chips as a function of drying method with the use of heat pump (HP) alone or combined with far infrared radiation (FIR) at 500, 1500 or 3000 W.

Properties	HP	HP+500FIR	HP+1500FIR	HP+3000FIR
Moisture content	18.1±0.023 [a]	16.9±0.011 [a]	12.1±0.014 [b]	11.5±0.015 [b]
Shrinkage(%)	75.44±2.34 [a]	73.52±2.65 [a]	74.88±3.05 [a]	77.67±2.88 [a]
Rehydration	2.43±0.06 [b]	2.67±0.03 [b]	3.55±0.07 [a]	2.08±0.05 [c]
Hardness(N)	60.53±2.31 [b]	77.36±3.03 [a]	77.15±2.88 [a]	80.11±3.15 [a]
Brittleness (No. of peak)	10.12±1.28 [c]	13.35±1.54 [b]	16.31±1.55 [a]	13.47±1.62 [b]
L*	58.90±1.87 [c]	64.13±1.98 [b]	66.98±1.45 [a]	58.34±1.03 [d]
a*	5.19±0.42 [ab]	4.73±1.37 [ac]	3.98±0.25 [cd]	5.43±0.22 [a]
b*	26.39±0.90 [b]	27.37±1.06 [b]	28.17±0.99 [b]	40.12±0.83 [a]
ΔE*	26.89±0.79 [b]	23.85±0.46 [c]	22.61±0.62 [c]	37.20±0.84 [a]

Values are means ± standard deviation (for shrinkage and rehydration, n=3; for hardness, brittleness, L, a, b, and ΔE, n=12).
Different letters in the same row indicate significant differences (P<0.05 using LSD).

3.5. Hardness and Brittleness

The hardness values of Iron Yam chips dried by HP+FIR were significantly higher (P <0.05) than that of samples dried by HP only. In addition, the effects of FIR on hardness were more obvious with increase in the power supplied to the FIR rods, which can be explained by the puffing caused by the rapid evaporation of water from the inside tissue architecture caused by FIR absorption [31]. Besides, FIR can speed up the drying rate, and at the same time accelerate the loss of moisture, so it is easy to form a relatively hard surface for Iron Yam chips.

From Table 1 we can also see that the brittleness of Iron Yam chips dried by HP+FIR increased significantly compared with single heat pump drying (P<0.05). Especially for HP+1500FIR, Iron Yam chips had a maximum brittleness which was significantly different (P<0.05) from the other two FIR assisted heating treatments. It was possible due to the formation of more open organizational structures the production of lager

internal pores, and then more and the resulting better quality when the FIR power was set as 1500W.

3.6. Color

The fruit color can be easily changed during the drying process, which is one of the negative quality attributes that affects customers' perceptions of dried products [6]. The results of color measurement for Iron Yam chips were shown in Table 1. The initial values of L_0^*, a_0^* and b_0^* for fresh Iron Yam chips before drying were 78.67, -3.13 and 10.17 respectively. The lightness (L^*) of Iron Yam chips dried by four drying methods decreased obviously compared to the above values,, and differed significantly from each other (P<0.05). HP+1500FIR treatment gave the highest L^* value, and HP+3000FIR produced the lowest. After drying, a^* values of samples increased, and HP+1500FIR treatment provided the less increase compared to the other three drying methods. The b^* values of Iron Yam chips increased in varying degrees for all drying treatments, however, there were no significant differences among HP, HP+500FIR, and HP+1500FIR (P>0.05). Table 1 showed that after drying the browning reaction of Iron Yam chips increased. In present study, HP+1500FIR treatment provided the smallest ΔE^* value, and HP+3000FIR gave the largest.

Moisture migration rate directly influence the color changes of drying products. In the drying process, the moisture evaporates from the material surface to the drying chamber; besides, internal moisture is transferred from the center of the material to its surface as well. The color of the dried fruit generally changes due to the browning reaction, which is always associated with the Maillard reaction [6]. In this paper, different thermal gradient caused by different FIR power led to different moisture migration rates from interior to the surface of Iron Yam chips. It can be speculated that, in the case of HP+500FIR and HP+1500FIR, Iron Yam chip surface was protected by a layer of water film, which reduced the rate of Maillard reaction, restrained the color degradation, and resulted in smaller color change. In case of HP+3000FIR, however, water film on Iron Yam chip surface was difficult to form, consequently browning reaction was intensified. As a result, the changes of lightness, redness/greenness and total color difference of Iron Yam chips dried by HP+3000FIR were the biggest compared to other three drying methods (HP, HP+500FIR, HP+1500FIR).

3.7. Energy Consumption

The results of energy consumption for Iron Yam chips by different drying treatments were shown in Table 2. It is clearly seen that energy consumption decreased when FIR was combined with HP drying and when the power supplied to FIR increased. Under our experimental condition, compared with HP treatment, the total energy consumption of HP+500FIR saved 21.53%, and in the case of HP+1500FIR and HP+3000FIR the values were 41.78% and 44.08%, respectively, which meant remarkable energy-saving effect. It should be pointed out that, there exist relationships between energy-saving

extent and numbers of samples, the larger the amount of samples, the more significant energy-saving effect.

Table 2. Energy consumption in the drying of Iron yam chips with the use of heat pump (HP) alone or combined with far infrared radiation (FIR) at 500, 1500 or 3000 W

Properties	HP	HP+500FIR	HP+1500FIR	HP+3000FIR
Energy consumption (kWh/kg water)	7.85±1.13 [a]	6.16±1.32 [b]	4.57± 1.16 [c]	4.39 ±1.05 [c]

Values are means ± standard deviation (n=3).
Different letters in the same row indicate significant differences (P<0.05) using LSD.

4. Conclusion

FIR in combination with heat pump drying helped to increase the drying rate and decrease the degree of the Maillard reaction. Compared with the Iron Yam chips dried only by HP, the surface water loss rate and hardness of samples treated by HP + FIR were increased, and there was a positive correlation with the FIR intensity. Moisture diffusion coefficients, calculated by Fick's second law for an infinite slab, ranged from $2.84 \times 10^{-9} m^2 s^{-1}$ to $8.21 \times 10^{-9} m^2 s^{-1}$ and increased with increasing FIR power. HP+1500FIR resulted in desired moisture ratio, the smallest shrinkage of dried Iron Yam chips, the highest rehydration percentage, and the smallest changes of color. One possible reason is that when the samples dried by HP+FIR at 1500W, the organizational structure of the dried Iron Yam chips were more open with more internal porosity. The overall energy consumption of the combined drying process was significantly decreased with the increase in the power supplied to the FIR heaters.

The present study provides a possible application of FIR combined with HP drying as an efficient drying process for Iron Yam chips, and the optimization of Iron Yam quality during drying process requires more investigations.

Acknowledgements

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