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Experimental Determination of Transport Parameters of Dragon Fruit Slices by Infrared Drying

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ABSTRACT

Infrared drying is an advanced drying method that preserves the nutritional value of the dried object. Currently, dragon fruit drying on a static tray by hot air circulation reveals disadvantages of long drying time and ununiform moisture distribution. In this study, Vietnam red dragon fruit was dehumidified in a vertical cylindrical infrared dryer. The drying mode includes radiation intensity in the range of 4 to 6 kW/m^2 and air velocity in the range of 1 to 3 m/s to investigate moisture transfer parameters and vitamin content in dragon fruit. The drying time was fixed at 10 hours to evaluate the final moisture content and vitamin contents. Henderson and Pabis drying model was adopted with the coefficient of determination greater than 0.98. Results show that the moisture diffusivity in the infrared drying was achieved in the range of 2.3e-9 to 3.9e-9 m^2/s. Moisture transfer coefficient of the dragon fruit varied in the range of 4e-5 to 1.2e-4 m/s. The Biot number in the drying by an infrared lamp ranged from 40 to 80. Vitamin C in dried dragon fruit has a high content of up to 13.5 mg/100 g. The current dragon fruit drying by infrared lamp reveals negligible surface resistance to mass transfer. The infrared drying of dragon fruit is a feasible alternative to preservation. Also, seeking of an optimal tray rotation speed may be further improvement of the drying rate.

1. Introduction

Vietnam is one of the countries with long-standing agriculture. Agricultural products are rich and diverse with large output. Therefore, preserving agricultural products after harvest is essential. Post-harvest technology plays a crucial role in the economy. It not only ensures food security for each country but also for the whole world. Therefore, the development of post-harvest technology, especially freezing technology, fermentation technology and drying technology, plays a key role in preserving food products against factors that can lead to spoilage, prolonging shelf life, consumption and trade [1]. These are extremely important in stabilizing the development of the country's economy [2,3]. Dragon fruit is one of the popular fruit trees in Vietnam, with a relatively large output. Dragon fruit products are mainly consumed domestically in fresh and raw products. To increase the export value of dragon fruit products, technology is necessary to make products of good quality for

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export and higher profits [4]. To do this, it is necessary to have a product preservation method in which the cold storage method (for export of fresh ingredients) and the drying method are widely used.

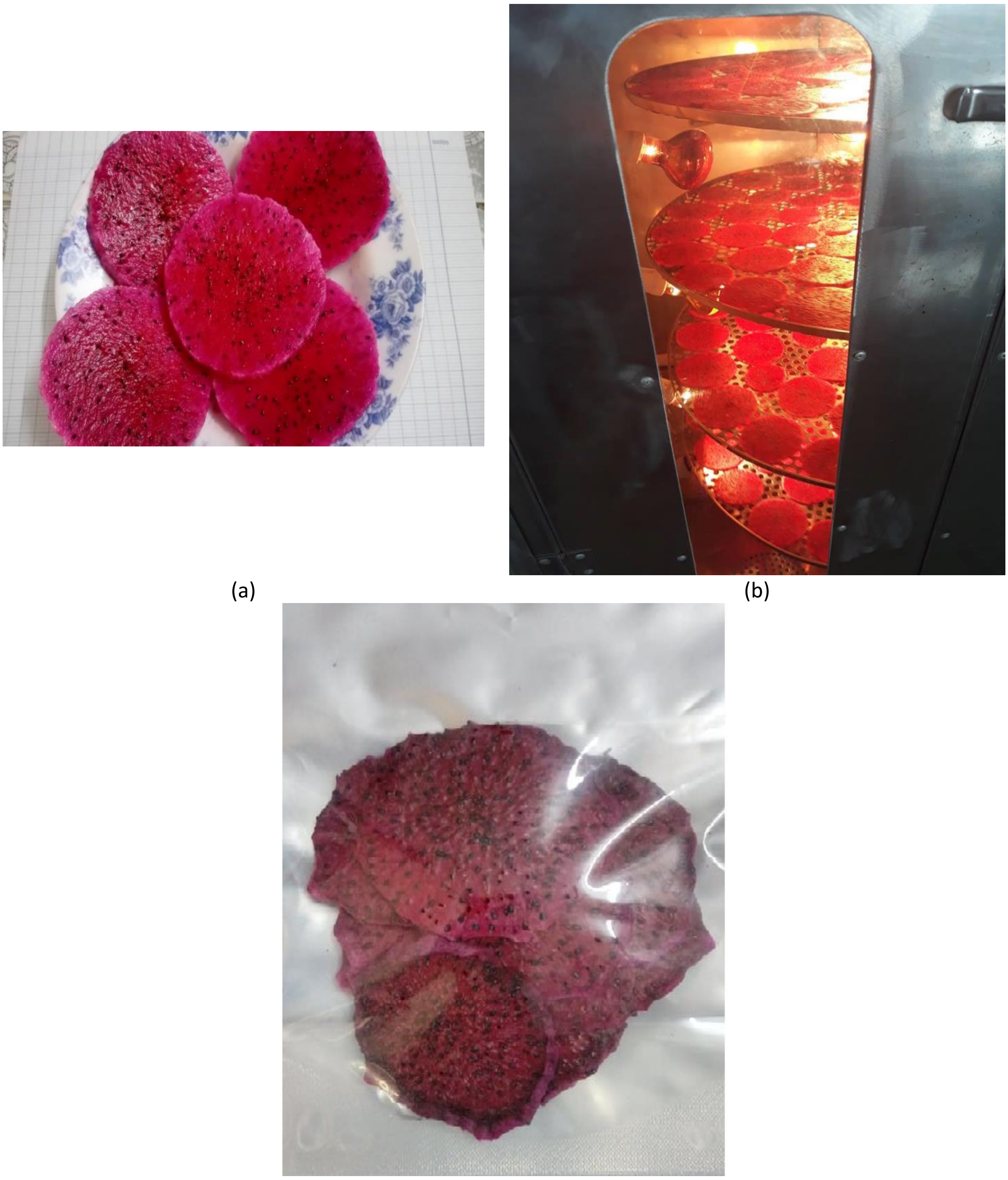
Infrared drying is one of the types of high-tech dryer. A product dried by infrared dryers has advantages such as the product obtained after the infrared drying process has the same quality as the fresh product. The drying process does not contaminate food. Infrared drying technology helps to shorten the production time. This method is entirely free from special catalysts (chemicals) impact. Infrared rays can also kill insects and sterilize dried products [5]. Nindo *et al.,* [6] designed and tested a vibration-assisted infrared dryer with a radiation intensity of 3100 to 4290 W/m^2 and a 12 to 16 mm grain depth. They found that grain depth had no significant effect on the drying rate of all three rice kinds used in the study for this thickness and for a certain intensity of infrared radiation. Other studies on the drying of onions by infrared radiation included the works of Sharma *et al.,* [7] and Kumar *et al.,* [8]. The moisture diffusivity of the onion ranged from 0.211e-10 to 0.723e-10 m^2/s [7]. The characteristic parameters of moisture transfer in drying include drying constant, moisture diffusivity, and Biot number. The drying constant represents the drying rate of a moist object. The moisture diffusivity quantifies the mass diffusion through the material. The Biot number indicates the rate of moisture transfer at the surface of the object compared to the rate of moisture diffusion inside the object. These parameters can be deduced from the drying model of Henderson and Pabis which shows the relationship between the moisture content with the drying constant and time. In most studies, it is clear that drying temperatures that are too high and or drying for a long time are detrimental to onion quality. Many other studies have been done on infrared radiation drying for fruits and vegetables such as Hebbar *et al.,* [9] with carrot and potato drying, Toğrul [10] with carrot drying, and Afzal and Abe [11] with potato drying. The main method of processing dried fruits and vegetables is by slicing and spreading them on trays made of wire mesh or flat metal plates. Raj and Dash [12] recently dried dragon fruit using microwave convective drying. They observed that the color change was insignificant and nutrition facts were enhanced.

In this study, a novel infrared dryer used to dry red dragon fruit was studied for mass transfer characteristics. The dryer consists of a vertical cylinder. Sliced dragon fruit is placed on rotating trays. Infrared lamps supply the heat source. The effects of infrared intensity and air velocity on drying mechanisms were examined.

2. Experimental Description

2.1 Material Preparation

Dragon fruits were purchased at the local market and then brought to the Industrial University of Ho Chi Minh City transport phenomena laboratory. Raw dragon fruit must be fresh and medium ripe. Dragon fruit was peeled to get the dragon fruit flesh. The dragon fruit flesh was sliced 5 mm in thickness as shown in Figure 1(a) and then put in the drying tray. Due to the natural shape of the dragon fruit, a slice had diameter in the range of 60 mm to 80 mm. Each tray contained 1.8 kg of dragon fruit and was evenly distributed as shown in Figure 1(b). The infrared dryer consisted of 4 rotating trays, each with a diameter of 0.5 m. These circular trays rotated around an axis with a fixed rotation speed so that the dragon fruit was evenly dried. The infrared lamps were mounted on the wall of the drying chamber. Each lamp had a nominal power of 75 W. The radiant intensity of the halogen lamp was adjusted by a dimmer to vary the emitted power. Air was drawn from the bottom to the top of the chamber by an axial fan to enhance convection heat transfer and moist removal in the chamber. The revolution number of the fan is variable to adjust the air velocity. The air velocity was measured using an airflow meter PCE-007. The mass of dragon fruit is automatically weighed every 60-minute interval to estimate instantaneous moisture content. The drying interval time was specified by means of the long drying time of dragon fruit and data acquisition. Experiments were carried out at different radiation intensities and air velocities at the same drying time of 10 hours to evaluate the final moisture and nutrition facts. Figure 1(c) shows dragon fruit dried in the infrared dryer and vacuumed in a plastic bag for storage. Mathematical models to deduce drying characteristics, including drying constant, moisture diffusivity, moisture transfer coefficient, and Biot number, were presented in the following sub-section.



(a) (b)

(c)

Fig. 1. Red dragon fruit drying; (a) sliced fresh dragon fruit, (b) infrared drying chamber, (c) dried dragon fruit

2.2 Data Reduction

Dry basis moisture content (M) was determined from the ratio of the weight of water to the weight of dry dragon fruit in which the weight of dry dragon fruit was evaluated in a dryer at the temperature of 105°C until the weight of dragon fruit was constant as per oven drying method. The moisture ratio (Y) was calculated from the dry basis moisture content at each interval (M(t)) to the initial moisture content (M_i) [13]

$$Y = \frac{M(t)}{M_i} \tag{1}$$

It is noted that the equilibrium moisture content was neglected in Eq. (1) due to its relatively small value to M(t) or M_i [14]. Initial moisture of the dragon fruit was M_i = 5.667 kg water per kg solid. At each drying condition, i.e., infrared intensity and air velocity, a moisture ratio curve with time (Y-t) is plotted. Ten thin layer drying models including Newton model, Page model, modified Page, Henderson and Pabis model, modified Henderson and Pabis model, Midilli *et al.,* model, logarithmic model, two-term model, two term exponential model, Hii *et al.,* model were tested in preliminary experiments to determine a suitable model [15,16]. The results showed that the Henderson and Pabis model had the largest coefficient of determination (R^2). Therefore, this model was selected in this study. Three replicates were experimented per drying condition. The reported result in this paper was an arithmetic mean value. The regression function by least square method of the drying curve was fitted using the Henderson and Pabis drying model as follows [17]

$$Y = a\exp(-St) \tag{2}$$

where "a" is the lag factor and S was the drying constant [18].

The moisture diffusivity (D) of the dragon fruit can be computed by the following correlation with assumptions of uniform initial moisture content, minor external resistance to heat and mass transfer, no shrinkage and even moisture diffusivity [16,19,20]

$$D = 4SL^2 / \pi^2 \tag{3}$$

where *L* is the half slab thickness of the dragon fruit slice.

Heat transfer coefficient (h_t) may be calculated by the Nusselt number (Nu) equation of Pohllhause as follows [21,22]

$$Nu = 0.664Re^{0.5}Pr^{1/3} \tag{4}$$

$$h_t = \frac{Nu \times k}{2L} \tag{5}$$

where Re and Pr are respectively Reynolds number and Prandtl number of the airflow.

The Reynolds number was defined as

$$Re = 2LV\rho / \mu \tag{6}$$

where V is air velocity. ρ, k, and μ are air density, conductivity, and viscosity, respectively.

Moisture transfer coefficient (h_m) can be found by the heat and mass transfer analogy as [23]

$$h_t / h_m = \rho c_p \left(Sc / Pr\right)^{1-n} \tag{7}$$

where Sc is the Schmidt number and n is a constant. The *n* value of 1/3 is assigned for drying applications [23].

The Schmidt number was defined as

$$Sc = \frac{\mu}{\rho D} \tag{8}$$

Moisture transfer rate to moisture diffusivity rate was also estimated by means of mass transfer Biot number (Bi) as [24]

$$Bi = \frac{h_m L}{D} \tag{9}$$

3. Results and Discussion

Figure 2 presents the drying curves that fit according to the drying model of Henderson and Pabis at each infrared intensity (I) and air velocity (V). As the drying conditions are increased, the moisture ratio decreases. The effect of infrared intensity was more dominant than the effect of air velocity. After 10 hours of drying, the highest drying condition yields a moisture ratio of about 0.03, and the smallest drying condition has a moisture ratio of 0.13. Table 1 presents the model coefficients with the investigated drying conditions. The coefficient of determination (R^2) was greater than 0.98 for all cases. This confirms the reliability of the Henderson and Pabis model in predicting dragon fruit drying by the infrared dryer. The drying constant (S) represents a moist material's heat and mass transport capacity per unit of time. The largest drying constant of 9.231e-5 s^{-1} can be observed at the highest drying condition. The drying constant of dragon fruit was low compared to other materials, e.g., broccoli [13]. This was because fresh dragon fruit's water was quite large. The water in the dragon fruit was in the form of suspension liquid; thus, the drying rate was low.

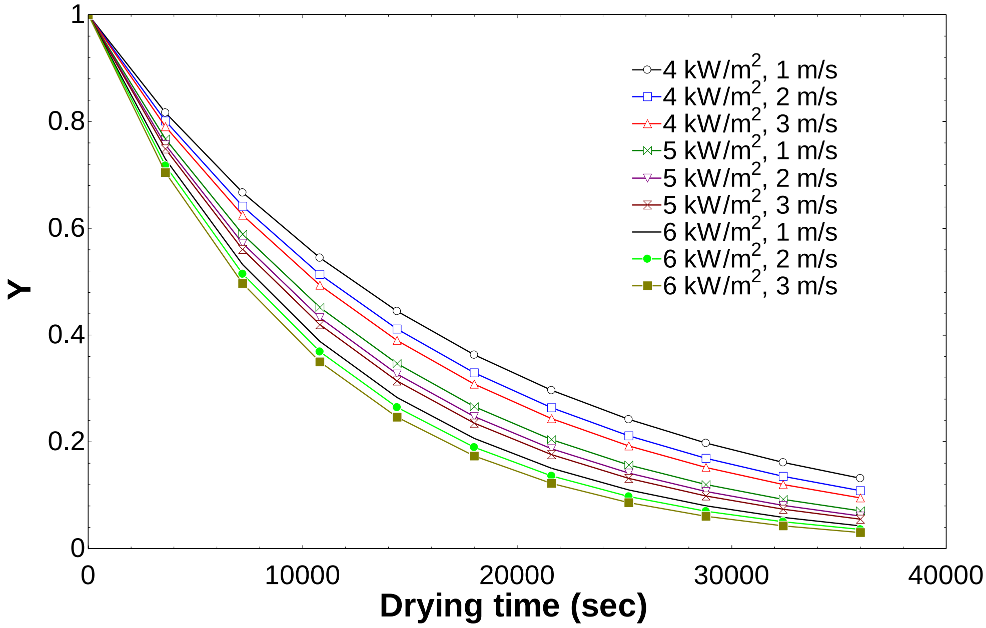


Fig. 2. Drying curves under various drying conditions

Table 1
Coefficients of Henderson and Pabis drying model

No.	I (kW/m^2)	V (m/s)	S (1/s)	a	R^2
1	4	1	0.00005627	1.014	0.9842
2	4	2	0.00006169	1.043	0.9865
3	4	3	0.00006541	1.054	0.9907
4	5	1	0.00007356	1.035	0.9820
5	5	2	0.00007762	1.064	0.9852
6	5	3	0.00008045	1.083	0.9855
7	6	1	0.00008765	1.073	0.9807
8	6	2	0.00009231	1.035	0.9896
9	6	3	0.00009732	1.048	0.9835

Figure 3 shows the effect of drying conditions on moisture diffusivity. The moisture diffusivity varies in the range of 2.3e-9 to 3.9e-9 m^2/s. Moisture diffusivity is the transfer rate of water molecules in moisture objects to different directions per unit of time [25]. When increasing drying conditions, the moisture diffusivity rises due to the increase in vapor pressure gradient and molecular motion, which results in high moisture diffusion to the object's surface [19,26]. The effect of infrared intensity is more pronounced than air velocity. Because the infrared source is the main driving force to conduct moisture to the object's surface. The infrared waves travel through air and meet drying objects where water is absorbed and transformed into vapor. The moisture diffusivity for the dragon fruit slices at air velocity of 1 m/s and infrared intensity of 6 kW/m^2 was 3.556e-9 m^2/s which increased to 3.947e-9 m^2/s when air velocity was increased to 3 m/s. The increase in air velocity speeded up the cooling effect, reducing the temperature at the surface of the dragon fruit slices thus decreasing the vapor pressure of water or the driving force for moisture transfer. The moisture transfer coefficient of the dragon fruit in the infrared drying chamber is shown in Figure 4. The moisture transfer coefficient represents the moisture transport rate from the object's surface to the airflow, which was one of the most significant parameters in drying. Moisture transfer coefficient increases with drying conditions and ranges from 4e-5 to 1.2e-4 m/s. The effect of the air velocity was more noticeable. Larger velocity results in better water removal from the moist object.

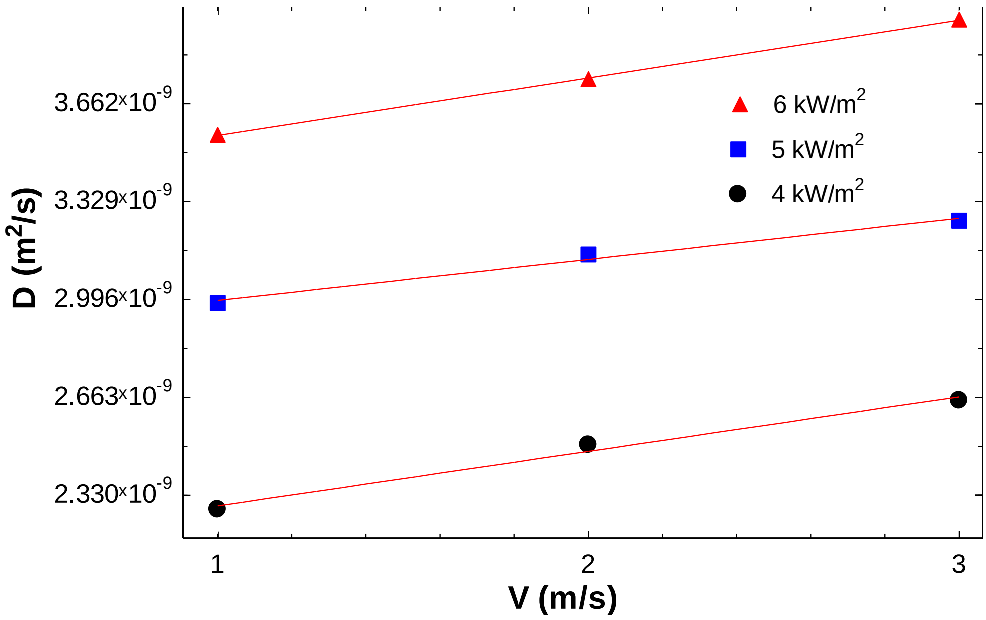


Fig. 3. Variation of moisture diffusivity with drying conditions

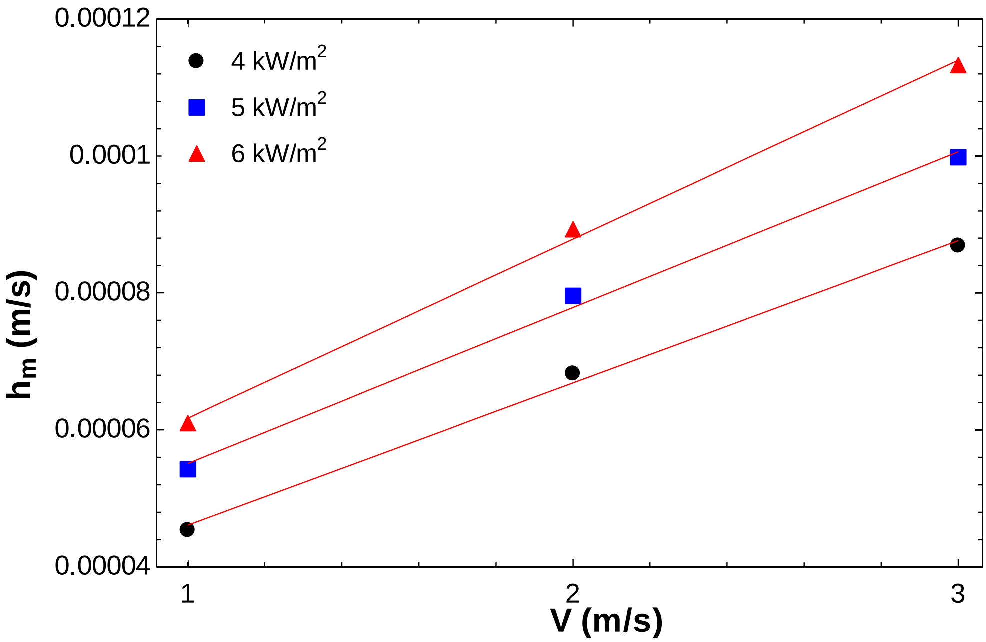


Fig. 4. Variation of moisture transfer coefficient with drying conditions

Figure 5 shows the variation of Biot number with drying conditions. The Biot number indicates the ratio of the internal resistance to the external resistance of a drying object. Usually, the Biot number varies in the range of 0.1 to 100. As can be seen in Figure 5, the Biot number greater than 40 exhibits negligible surface resistance to mass transfer [27]. In other words, the primary resistance was moisture diffusion inside the dragon fruit. As the air velocity increases, the moisture transfer coefficient at the surface increases; thus, the Biot number increases. In contrast, when increasing infrared intensity, the Biot number decreased due to the increase in moisture diffusivity. Furthermore, when increasing the electromagnetic radiation, the temperature inside the object was high, creating a temperature gradient in the same direction as the moisture gradient in the object, thereby reducing the internal resistance.

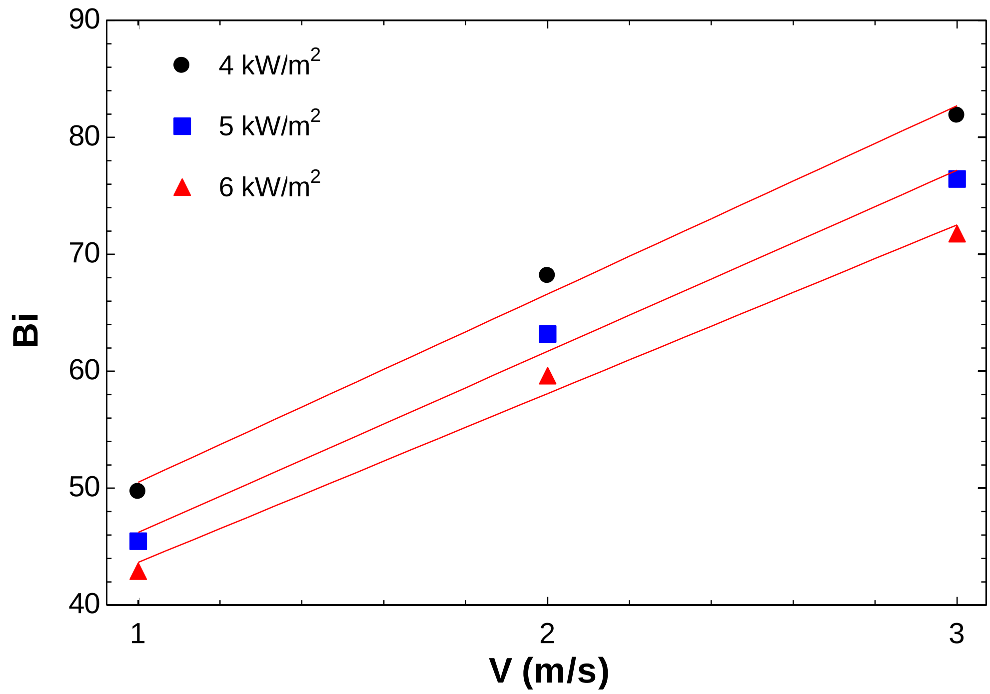


Fig. 5. Observed Biot number at different drying conditions

The critical vitamins of dragon fruit, such as vitamin C, vitamin B and a few amino acids, are retained in large amounts during the drying process because they exist in the seeds of the dragon fruit. This is very important for dragon fruit after drying because it preserves almost all the nutritional components in fresh dragon fruit. Figure 6 presents the nutritional composition analysis of dragon fruit after 10 hours of drying with two infrared intensities and the comparison with fresh dragon fruit. Vitamin C and vitamin B3 in the fresh dragon fruit were tested using the methods of AOAC2012.21 mod. and EN 15652 2009 mod., respectively, by Eurofins Sac Ky Hai Dang Co., Ltd. Vietnam. Vitamin C and vitamin B3 in the dried dragon fruit were tested using the methods of CASE.SK.0108 (HPLC) and CASE.SK.0083 (LC/MS/MS), respectively, by the center of analytical services and experimentation (CASE) in Ho Chi Minh city, Vietnam. Analytical results show that vitamin C content is higher than vitamin B3. After drying, the amount of vitamin B3 decreased due to the high temperature of the dried product [28,29]. Dried dragon fruit has a negligible water content. Therefore, the amount of vitamin C of the dried dragon fruit was higher than that of fresh dragon fruit. At the same drying time, higher infrared intensity achieves greater dragon fruit density. Therefore, the vitamin content increases with infrared intensity. Visual estimation of dried dragon fruit implied that the infrared drying keeps the bright red color close to that of fresh dragon fruit, as shown in Figure 1(c).

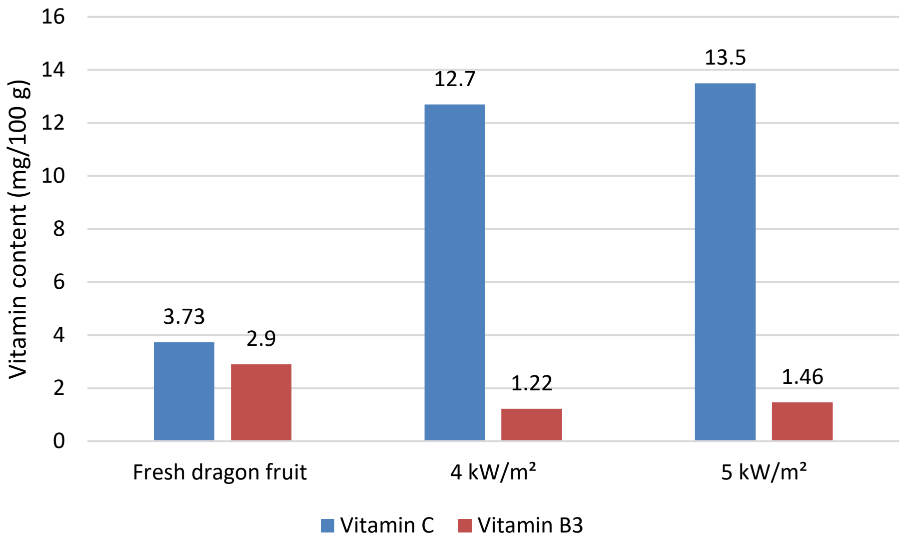


Fig. 6. Nutrition facts after 10 hours of drying

4. Conclusions

Drying dragon fruit in a vertical cylinder powered by an infrared lamp was presented in this paper. The parameters of moisture transport, drying kinetics and nutritional analysis was obtained from the drying experiment. The main findings from the study are stated as follows

i. Infrared intensity has a significant influence on moisture diffusivity. The moisture diffusivity in infrared drying combined with convection is in the range of 2.3e-9 to 3.9e-9 m^2/s.
ii. Moisture transfer coefficient increases with infrared intensity and air velocity. Variation of dragon fruit moisture transfer coefficient is in the range of 4e-5 to 1.2e-4 m/s.
iii. The Biot number in infrared drying is greater than 40, which shows that the resistance inside the drying object was dominant.
iv. Vitamin C content in dried dragon fruit accounts for a high percentage and increases with infrared intensity due to high dragon fruit density for a fixed drying time.

Further research may examine the effect of tray rotation speed on drying characteristics in search of the optimal speed to achieve high nutrient and transport parameters.

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