

## Study on Calculating, Designing and Manufacturing the Smart Infrared Drying System

Linh Thuy Khanh Do<sup>1</sup>, Chau Thanh Tuan<sup>2</sup>, Vu Tran Khanh Linh<sup>1</sup>, Nguyen Tan Dung<sup>1\*</sup>

<sup>1</sup>Hochiminh City University of Technology and Education, Vietnam

<sup>2</sup>Soc Trang Vocational College, Vietnam.

\* Corresponding author. Email: [tandzung072@hcmute.edu.vn](mailto:tandzung072@hcmute.edu.vn); Tel: 0918801670

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### ABSTRACT

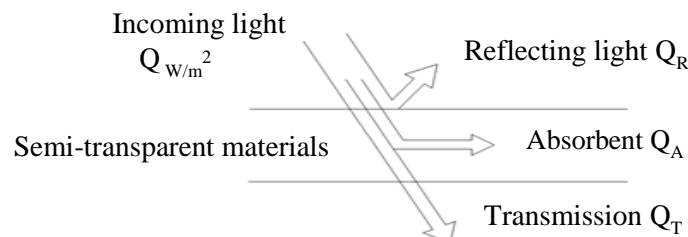
The infrared drying technology has been known as the energy saving technology. The infrared dried products keep their quality better than those dried by other normal methods. This research will present the results of calculating, designing, and manufactured the infrared drying system with the capacity of 12 kilograms materials per batch. The drying process is automatically controlled and measured by the computer program. After successfully manufactured, the drying system was used to dry the pineapple products with a thickness of 3 to 4 mm and followed by the drying modes: 69 °C of the drying temperature, 5 m/s of the rate of drying factors, and 5.0 hours of the drying time. The results showed that the energy cost was 2.013 kWh/kg of products lower than that of 3.8 kWh/kg of products dried by the normal dryings, the moisture content reached 9.96 %, reduced products cost, and prolonged the self-life. The dried pineapple showed the bright yellow, natural odors, and better quality than that dried by normal methods. Thus, the manufactured drying system can improve the post-harvest preserving matters of Vietnamese agricultural products and lead to high economic efficiency.

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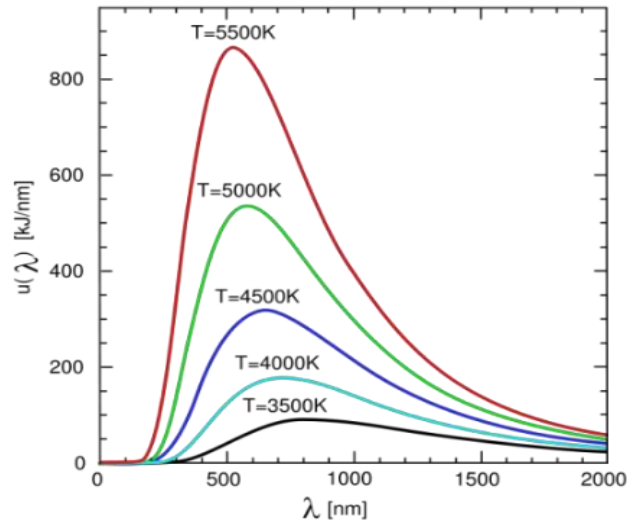
## 1. Introduction

Drying is the process that water is separated from moist materials at the certain conditions of temperature and pressure. The removal of water affects to food products: mass loss, delivery cost. The reduction of water activity leading to the loss of the microorganism living environment, prolonging the shelf life, and changes of rheology and sensory activities of food [1], [2], [3]. For the infrared drying technology, the infrared radiation rays, which have been used as the energy source, can be defined as the movement to the surface of any environment, the reflection, the absorbance, and the transmittance of the electromagnetic waves. If the radiations meet an object, they do only reflect or absorb or transmit independently, the object is called the absolute white-body, absolute black-body or absolute transparent-body, respectively. Generally, the natural objects, including all of food materials, are called grey bodies. It means that a portion of the radiations can transmit natural objects, the other portion can reflect. The effect of thermal radiations onto thickness limited objects or environment was described in Figure 1.



**Figure 1.** Absorbing, reflecting, and transmitting of a radiation through a size limited environment

The non-reflecting and transmitting surface is called the absolute black-surface or body. Based on the law of radiation, the radiation part emitted by the black-body is equal to that absorbed by the black-body. The Planck's law [2] described that the distribution of the radiation energy of the black-body depends on the wave variability. Moreover, the Wien's law can help to determine the wavelength of a monochrome radiation so that the radiation energy reaches the maximal value at a certain temperature.



**Figure 2.** The relationship between emission yield of the back-body and wavelengths

Figure 2, illustrated the Planck's and Wien's law, showed the relationship between emission yield of the back-body and wavelengths of monochrome radiations [2]. Based on the Planck's and Wien's law, they can help to find the wavelength of the infrared radiation reaching the maximal energy value. The wavelength can be applied to the drying technology by using infrared radiations to make the rate of vapors evaporation higher than that by using normal drying methods [2], [3]. Thus, it can shorten the drying process, enhance the producing capacity, and efficiency [2], [3]. According to Sanjay B. et al, the infrared drying is one of the most important methods applied in the food industry due to its advantages such as the small size of equipment, the rapid heat transfer, the energy-saving cost, the easy combination of heat transfer by convection, conductivity or microwaves [4].



**Figure 3.** Pineapple (*Ananas comosus*)

In this study, the Pineapple (*Ananas comosus*) was used as the initial material served for designing and manufacturing the infrared drying system. Besides, it was used for experiments to verify and evaluate the effectiveness of the infrared drying system. A pineapple, belong to mistletoe plants in the family Bromeliaceae, is a kind of the tropical edible fruit [5]. The multiple fruit is the combination of individual fruitlets on a single stalk. Multiple flowers are helically arranged along the axis forming a single fleshy fruit [5]. The pineapple is one of the most nutritious fruits riched in 85.66 % of water, 13.1 % of carbohydrate, 0.54 % of protein, 0.12% of lipid, 8 mg of phosphorus, 47.8 mg of vitamin C, and the Magnesium, Calcium, and Ferrous contain 12 mg, 13 mg, and 0.29 mg, respectively [6]. The advantages of pineapple fruit are it can decrease inflammatory and swelling reactions under the effect of bromelain, a typical enzyme in the fruit, body and liquid of pineapple [6]; it can aid digestion, relieve flatulence and constipation [7]. Besides, Vitamin C, beta – carotene in the fruit liquid can help human bodies from cardiovascular or exercise-induced asthma disease [8], [9].

Thus, the study on calculating, designing, and manufacturing of the infrared drying system can bring benefits not only for preserving of dried pineapple but also for the other agricultural products. It can help to guarantee the food security of the nation and the world.

## 2. Materials and Methods

### 2.1. Materials

For calculating, designing, and manufacturing the infrared drying system, pineapples were chosen as essential parameters: the initial and post-drying moisture, the specific mass of materials, the material input capacity, the hypothetical drying temperature and time, and the heat source. In this study, the pineapples were collected from the certain place, washed, cut into a thickness of 3 ÷ 4 mm, blanched, put into trays and dried by the infrared drying system.

### 2.2. Technological parameters of the infrared drying system

- The initial moisture of materials: 85.66%; post-drying moisture of pineapple products: 9.96 %.
- The material input capacity of the system: 12 kg of materials/batch.
- Controlled drying temperature: 40 ÷ 80 °C, the optimal temperature of the materials: 69 °C.
- Rate of drying factor: 2 ÷ 12.5 m/s, the optimal rate of the materials: 5 m/s.
- Drying time: 4 ÷ 12 h, the optimal time of the materials: 5h.
- The maximal capacity: 5.93 kg of moisture per 7 h; energy cost for 1 kg of moisture: 2.5 ÷ 3 kWh; at the optimal drying conditions, the energy cost is 2.013 kWh/kg. The system containing the automatic controller that can display drying temperature and time, and the rate of drying factor [10].
- The heat source: infrared lamp.

### 2.3. Calculating methods

#### 2.3.1. Calculating size of the drying chamber

- Volume contained by products:  $V_{pro} = \frac{G_{pro}}{\rho}$  (1)

- Choose the suitable size of trays, the volume contained by a tray:  $V_t = a_t \times b_t \times h_t$  (2)

From the calculating results, the drying chamber was made with the suitable capacity, the optimized area, and the drying space.

#### 2.3.2. Calculating heat for drying system

- Heat for drying system was performed by the equation [11], [12]:

$$Q = Q_1 + Q_2 + Q_3 + Q_4 + Q_5, \text{ (kJ)} \quad (3)$$

With:

$Q_1$  (kJ) – heat makes moisture to be evaporated from the initial room temperature ( $t_{ini} = 25$  °C) to the optimal drying temperature ( $t_{opt} = 65$  °C);

$Q_2$  (kJ) – heat warms rest of the non-evaporating water in the internal products;

$Q_3$  (kJ) – heat warms the product's internal dry matter;

$Q_4$  (kJ) – heat warms product trays;

$Q_5$  (kJ) – losing heat through the walls of drying chamber.

$Q_1, Q_2, Q_3, Q_4,$  and  $Q_5$  were calculated as following:

- Outcome product capacity [11,12]:  $G_2 = G_1 \cdot \frac{100 - W_1}{100 - W_2}$ , (kg/batch) (4)

Where:

$G_1$  (kg/batch) – the material input capacity of the drying system;

$W_1$  (%) – the initial moisture of materials;

$W_2$  (%) – post-drying moisture of products.

- Heat makes moisture in the materials to evaporate [10]:

$$Q_1 = G_w \cdot C_{pa} \cdot (t_{opt} - t_{ini}) + G_w \cdot r_v, \text{ (kJ)} \quad (5)$$

Where:

$C_{pa}$  (kJ/kg) – the average specific heat of products earlier drying;

$G_w$  (kg/batch) – the mass of evaporating water of materials in a batch;

$r_v$  (kJ/kg) – the latent heat of vapor water.

- Heat warms the non-evaporating water in the internal products [13]:

$$Q_2 = G_{wr} \cdot C_w \cdot (t_{opt} - t_{ini}), \text{ (kJ)} \quad (6)$$

Where:

$G_{wr}$  (kg/batch) – the mass of rest water after drying;

$C_w$  (kJ.kg<sup>-1</sup>.K<sup>-1</sup>) – the specific heat of water inside the material.

- Heat warms the dry matter in the internal products [13]:

$$Q_3 = G_{dm} \cdot C_{dm} \cdot (t_{opt} - t_{ini}), \text{ (kJ)} \quad (7)$$

Where:

$G_{dm}$  (kg/batch) – the mass of the material dry matter in a batch;

$C_{dm}$  (kJ.kg<sup>-1</sup>.K<sup>-1</sup>) – the specific heat of dry matter inside the material.

- Heat warms product trays (losing heat via trays) [13]:

$$Q_4 = n_t \cdot G_t \cdot C_{pt} \cdot (t_{opt} - t_{ini}), \text{ (kJ)} \quad (8)$$

Where

$n_t$  – the number of trays in the drying chamber;

$G_t$  (kg) – mass of a tray;

$C_{pt}$  (kJ.kg<sup>-1</sup>.K<sup>-1</sup>) – specific heat of a tray.

- Losing heat through the walls of drying chamber [14]:

$$Q_5 = Q_{51} + Q_{52} = \frac{F_{51} \times (t_{opt} - t_{ini})}{\frac{\delta_1}{\lambda_1} + \frac{\delta_2}{\lambda_2}} + \frac{F_{52} \times (t_{opt} - t_{ini})}{\frac{\delta_1}{\lambda_1} + \frac{\delta_2}{\lambda_2}}, \text{ (kJ)} \quad (9)$$

Where:

$F_{51}, F_{52}$  (m<sup>2</sup>) – the sum of the area of top side and under side of the drying chamber, respectively;

$\delta_1, \delta_2$  (mm) – the thickness of the wall material, and the heat insulation layer of drying chamber, respectively;

$\lambda_1, \lambda_2$  (W/(m<sup>2</sup>.K)) – the thermal conductivity coefficient of the wall materials, and the heat insulation layer, respectively.

### 2.3.3. Calculating and selecting infrared lamps

After calculating the Q value by the equation (3), the capacity of infrared lamps was calculated by the following equation (10) [13]:

$$P = \frac{Q}{\mu \cdot \tau \cdot 3600}, \text{ (kW)} \quad (10)$$

Where:

Q (kJ) – the total heat of the drying system;

$\mu$  (%) – the efficiency of the infrared lamps;

$\tau$  (s) – the assumption drying time.

- The number of necessary lamps for the drying system [13]:

$$N = \frac{P}{P_{\text{lamp}}}, \text{ (item)} \tag{11}$$

#### 2.4 Methods of designing and manufacturing the infrared drying system

In this study, AutoCAD version 2018 (Autodesk Inc., US) was used to design the technical drawings of the drying system, and the detail drawings for each equipment. Besides, some mechanical processing methods were used to manufacture the system such as: milling, planing, bending, grinding, mounding, welding, and drilling...

#### 2.5. Methods of assessment of the system quality by experiment

Quality of the post-drying products is one of the most important factors to assess the efficiency of the drying system, and to adjust technological parameters. The two selected outcome parameters are energy cost per kilogram  $y_1$  (kWh/kg), and the moisture content of the post-drying pineapple products  $y_2$  (%).

- The energy cost per a kilogram product [10]:  $y_1 = \frac{P \cdot \tau}{G}$ , (kWh/kg) (12)

Where:

$G$  (kg) – mass of drying products;

$\tau$  (h) – drying time;

$P$  (kW) – consumption power capacity.

- The moisture content of products was calculated by the equation [10]:

$$y_2 = 100 - \frac{G_{\text{ini}}}{G_{\text{fin}}} (100 - W_0) \tag{13}$$

Where:

$G_{\text{ini}}$  (g) – mass of moist materials;

$G_{\text{fin}}$  (g) – mass of final drying products;

$W_0$  (%) – moisture content of materials.

#### 2.6. Experimental optimization

In this research, the selected infrared drying mode is the continuous drying, and the rate of the drying factor are the constant as  $x_3 = 5$  m/s. Drying and optimizing of experiments were following steps [15]:

Problems are how to identify the optimal variants ( $x_1, x_2$ ) so that  $y_1$  reaches the minimal value (where  $x_3 = \text{const}$ ).

- Step 1: given value of  $x_2, x_3 = \text{const}$ , making experiments with the parameter  $x_1$  in range of [ $A_{x1}, B_{x1}$ ], variance range  $\Delta_{x1} = (B_{x1} - A_{x1})/n$ , so the values of experimental factors are:  $x_{10} = A_{x1}, x_{11} = A_{x1} + \Delta_{x1}, \dots, x_{1n} = A_{x1} + n\Delta_{x1} = B_{x1}$  [9]. See Table 1.

**Table 1.** Experiment with constant factors  $x_2, x_3$

$x_1$	$x_{10}$	$x_{11}$	.....	$x_{1n}$
$y$	$y_{10}$	$y_{11}$	.....	$y_{1n}$

Showing the experiment data in the diagram, the extreme value of  $y_{11\text{opt}}$  can be recognized at  $x_{11\text{opt}}$ .

- Step 2: give the values  $x_{11\text{opt}}, x_3 = \text{const}$ , making experiments with parameters  $x_2$  in range [ $A_{x2}, B_{x2}$ ], variance range  $\Delta_{x2} = (B_{x2} - A_{x2})/n$ , so the values of experimental factors are:  $x_{20} = A_{x2}, x_{21} = A_{x2} + \Delta_{x2}, \dots, x_{2n} = A_{x2} + n\Delta_{x2} = B_{x2}$  [9]. See Table 2.

**Table 2.** Experiment with factors  $x_{11opt}$ ,  $x_3 = const$

$x_2$	$x_{20}$	$x_{21}$	.....	$x_{2n}$
$y$	$y_{20}$	$y_{21}$	.....	$y_{2n}$

Showing the experiment data in the diagram, the extreme value of  $y_{12opt}$  can be recognized at  $x_{22opt}$ .

if  $y_{11opt} = y_{12opt}$ , ( $x_{11opt}$ ,  $x_{22opt}$ ,  $x_3 = 5m/s$ ) are the optimal experiences. However, in the real conditions, it is nearly not occur. Thus, the experiments will be carried out as the described steps in the narrower range  $[a_{xj}, b_{xj}] \subset [A_{xj}, B_{xj}]$ . The experimental data will be analyzed, assessed, and handled by Microsoft Excel software [15].

### 3. Results and Discussion

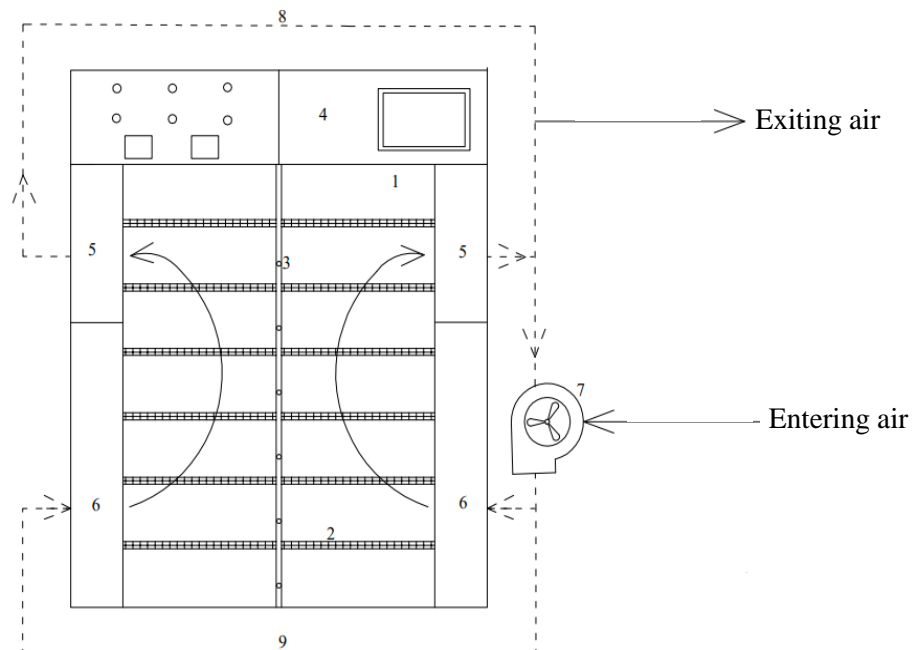
#### 3.1. Initial data served for calculating and designing the infrared drying system

To manufacture the infrared drying system, some initial data needed for calculating and designing the infrared drying system. The data were obtained from another research and chemical analysis and showed in Table 3.

**Table 3.** Initial parameters needed for calculating and designing

No.	Names	Values
1	Material input capacity	12 kg material/batch
2	Heat source	Infrared lamps
3	Drying materials	Pineapple
4	Drying temperature	65°C
5	Assumption drying time	4 hours
6	Initial moisture content of materials	85.66 %
7	Post-drying moisture content	10 %
8	Specific mass of materials	1061.48 kg/m <sup>3</sup>

#### 3.2. Calculating and designing the infrared drying system



**Figure 4.** The principle diagram of the infrared drying system

1. Drying chamber, 2. Drying trays, 3. Infrared lamps, 4. IoT controlling cabinet, 5. Air wind returning cabinet, 6. Air supplying cabinet, 7. centrifugal fan, 8. Entering air, 9. Exiting air

Figure 4 showed the principal diagram of the smart infrared drying system designed and manufactured with the input capacity of 12 kg material per batch. The system was used the combination of the thermal convection and the heat radiation to enhance the heat transferring efficiency during the drying period.

Based on the principles of the infrared drying system shown in Figure 4, applied the methods of the material and energy balance described in the 2.2, 2.3, the smart infrared drying system was calculated. The results were summarized in Table 4.

**Table 4.** Results of calculating and designing the infrared drying system with the capacity of 12 kg materials per batch

Parameters	Applied equations	Units	Results
Volume contained by products ( $V_{pro}$ )	(1)	$m^3$	0.01
Volume contained by the inox 304 tray ( $V_t$ )	(2)	$m^3$	$3.45 \times 10^{-3}$
Size of a tray (reality)			
- length	-	mm	575
- wide	-		300
- height	-		20
Number of trays ( $n_t$ )	-	Tray	12
Size of the drying chamber			
- length		mm	710
- wide			605
- height			800
Outcome product capacity ( $G_2$ )	(4)	kg/batch	1.91
Heat makes moisture to evaporate ( $Q_1$ )	(5)	kJ	25870.86
Heat warms rest of the non-evaporating water inside the products ( $Q_2$ )	(6)	kJ	31.79
Heat warms the dry matter inside the products ( $Q_3$ )	(7)	kJ	15.82
Heat warms product trays (losing heat via trays) ( $Q_4$ )	(8)	kJ	321.60
Losing heat through the walls of drying chamber ( $Q_5$ )	(9)	kJ	140.85
Total heat of the drying system ( $Q$ )	(3)	kJ	30814.06
Power capacity of infrared lamps ( $P$ )	(10)	kW	3.06
Number of necessary lamps for the drying system (the 250 W lamp was chosen) ( $N$ )	(11)	lamp	12

### 3.3. Manufacturing the smart infrared drying system

For the results in Table 5, the technical drawings of the smart infrared drying system were designed by using the AutoCAD software. Besides, the automatic measuring and controlling system was designed based on the technological requirements.

Then, based on the designed drawings, applied some mechanical processing methods such as: milling, planing, bending, grinding, mounding, welding, and drilling... and manufactured electrical circuits, the smart infrared drying system was produced. As a result, the drying system, has been completely finished and shown in Figure 5, with the technological mode:

- Capacity of the system: maximal 12 kg of materials per batch.
- Controllable temperature of drying environment:  $40 \div 80$  °C.

- Controllable drying time depended on kinds of moist materials, for other agricultural products, drying time can be  $4 \div 12$  h.
- Controllable rate of the drying factor:  $2 \div 12.5$  m/s.



**Figure 5.** The manufactured smart infrared drying system with the capacity of 12 kg of materials per batch

Technological parameters of the smart drying system, temperature of the drying environment and drying products, rate of the drying factor, and time of drying can be controlled automatically by computer programs and combined to IoT controlling via the Internet. Therefore, the drying process can be carried out to make the high-quality products, the moisture content reaches the requirement to increase the shelf-life of the products. In addition, the energy cost can be reduced to the minimal level, lead to reduce of the product cost, and increase the commercial competitions.

### **3.4. Experiments to assess the quality of the infrared drying system**

To evaluate the stable, and efficient working abilities of the smart infrared drying system, in this study, the pineapples were cut into the plate form with the thickness from  $3 \div 4$  mm to carry out the experiments. The pineapples were dried at variable technological modes. Some parameters, temperature of the drying environment, rate of the drying factors, and time of drying, were variant from ranges:

- Temperature of the drying environment:  $55 \div 75$  °C.
- Rate of the drying factors:  $3 \div 5$  m/s.
- Time of drying:  $5 \div 7$  hours.

Based on the experimental data, the experiments were optimized by the variable alternative methods described in 2.4. Results showed that in the optimal drying technological modes, if the thickness of materials was  $3 \div 4$  mm, the temperature of drying environment was  $69$  °C, the rate of drying factors was  $5$  m/s, and the time of drying was  $5$  hours. The post drying products were shown in Figure 6, the products have the bright yellow, natural odors, and have high quality. The quality is higher than that of products dried by normal drying methods, and the moisture content of the products reached  $9.96$  % lead to the increasing of the shelf-life. The drying energy cost reached the minimal level,  $2.013$  kWh/kg of products. It is lower than that of products dried by the normal drying methods ( $3.8$  kW/kg), and it reduced the product cost, increased competition, suited for commercialization and for the products'

export. This result is conformed to the finding of Sanjay B. Pawar, V.M. Pratape (2015) [4] that the infrared drying technology can be shorten drying time compared to that of other normal drying technology. The drying time can be shortened due to the heat transmission which is used to separate moisture in the drying, and can be combined of heat conduction, radiation, and convection. Therefore, the drying using the infrared radiation can improve the energy efficiency, the quality of products and the productivity as compared to those of the normal drying methods, as well as lead to the small size and weight of the equipment [4], [16], [17]. Figure 6 showed the final products dried through the smart infrared drying system manufactured in this study (Figure 5).



**Figure 6.** The infrared drying pineapple products

#### **4. Conclusions**

In this research, the smart infrared drying system was successfully manufactured with the capacity of 12 kg of materials per batch and working steadily and effectively. The technological parameters are controlled, measured automatically, and monitored by the program setting up on the computer. Besides, the drying processes were remotely controlled, monitored by IoT via the Internet that improve the convenience of usage and operation. The drying temperature was controlled from 40 to 80 °C, the drying time was set depended on kinds of moist materials or monitored from 4 to 12 hours in associated with other agricultural products, and the rate of drying factors were established from 2 to 12.5 meters per second.

The drying system was completely manufactured to solve the demands of post-harvested preserving issues. It can help reduce the cost of preservation for agricultural products in Vietnam, enhance the best quality products, decrease the drying time, saving the energy, and contribute the high economic efficiency for factories.

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**Linh Thuy Khanh Do, Msc.**

Department of Food Technology; Faculty of Chemical and Food Technology;  
HCM City University of Technology and Education, Viet Nam;  
No 01, Vo Van Ngan Street, Thu Duc District, HCM City.  
Phone: 0936699563  
Email: [dtklinh@hcmute.edu.vn](mailto:dtklinh@hcmute.edu.vn)



**Chau Thanh Tuan, PhD.**

Department of Aquatic Product Technology, Faculty of Aqua and Agriculture;  
Soc Trang Vocational College;  
No 176, Nam Ky Khoi Nghia Street, Soc Trang City, Soc Trang Province, Viet Nam;  
Phone: 0989298529;  
Email: [chauthanh tuan@gmail.com](mailto:chauthanh tuan@gmail.com)



**Vu Tran Khanh Linh, PhD.**

Department of Food Technology; Faculty of Chemical and Food Technology;  
HCM City University of Technology and Education, Viet Nam;  
No 01, Vo Van Ngan Street, Thu Duc District, HCM City.  
Phone: 0966955469  
Email: [linhvtk@hcmute.edu.vn](mailto:linhvtk@hcmute.edu.vn)



**Nguyen Tan Dzung, Associate Professor, PhD.**

Department of Food Technology; Faculty of Chemical and Food Technology;  
HCM City University of Technology and Education, Viet Nam;  
No 01, Vo Van Ngan Street, Thu Duc District, HCM City.  
Phone: 0918801670  
Email: [tandzung072@hcmute.edu.vn](mailto:tandzung072@hcmute.edu.vn); [tandzung072@yahoo.com.vn](mailto:tandzung072@yahoo.com.vn)