

STUDY AND MANUFACTURE OF THE LOW TEMPERATURE VACUUM DRYING SYSTEM IN PILLOT SCALE

NGHIÊN CỨU VÀ CHẾ TẠO HỆ THỐNG SẤY CHÂN KHÔNG NHIỆT ĐỘ THẤP DẠNG PILLOT

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ABSTRACT

This study will present results of calculating and designing the low temperature vacuum drying system in pillot scale. Based on that data, the lowtemperature vacuum drying system is made and automatically controlled by IoT (Internet of Things) in order to process and preservate food products as well as increase the value of post-harvest food products. The final result obtained is the low temperature vacuum drying system with automatic IoT that has a quality and technology parameters as follows: productivity of 5.3kg/batch; temperature of drying chamber of (0-55) °C; pressure of drying chamber under 6mmHg; time of drying process about (12-24 hours/batch). In addition, energy cost per kilogram of product in the low temperature vacuum drying compared with freeze drying is reduced about (25-35)%, the cost of this drying system is only half compared with the freeze drying system. Carrot is chosen to examine the quality of this system. As a result, the products have refined structure, the loss of β -carotene is less than 5%, the residual water content of product is less than 4%, the rehydration capacity of product (recovery yield) was over 98% and other sensory characteristics unchange.

Keywords: vacuum drying; vacuum drying machine; vacuum drying system; low – temperature vacuum drying system; vacuum drying equipment.

TÓM TẮT

Nghiên cứu này sẽ công bố kết quả tính toán, thiết kế hệ thống sấy chân không nhiệt độ thấp dạng pillot. Trên cơ sở dữ liệu đó đã chế tạo hệ thống sấy chân không nhiệt độ thấp, tự động điều khiển bằng IoT ứng dụng trong chế biến và bảo quản thực phẩm, cũng như làm tăng giá trị của các sản phẩm thực phẩm sau thu hoạch. Kết quả cuối cùng nhận được là hệ thống sấy chân không nhiệt độ thấp, tự động điều khiển bằng IoT có chất lượng với năng suất 5,3kg/mẻ, nhiệt độ môi trường sấy (0 – 55)°C, áp suất môi trường sấy có thể giảm dưới 6mmHg, thời gian sấy (12-24)giờ/mẻ, chi phí năng lượng cho 1kg sản phẩm giảm (25-35)% so với sấy thăng hoa, giá thành của một hệ thống sấy cùng năng suất chỉ khoảng ½ so với hệ thống sấy thăng hoa. Sản phẩm sau khi sấy trên hệ thống sấy này có chất lượng tốt, với carot thì độ tổn thất beta-caroten dưới 5%, độ ẩm dưới 4%, màu sắc mùi vị không thay đổi, khả năng hoàn nguyên đạt trên 98%.

Từ khóa: sấy chân không; máy sấy chân không; hệ thống sấy chân không; hệ thống sấy chân không nhiệt độ thấp; thiết bị sấy chân không.

1. INTRODUCTION

Vacuum drying is a dehydration process carried out in vacuum environment, pressure inside the moist material. The process is of drying chamber is under 1 at. Vacuum

drying consists of two categories: normal-temperature vacuum drying and low-temperature vacuum drying [1].

Normal-temperature vacuum drying is carried out in condition as follows: the temperature of drying chamber is about (40 ÷ 70)°C, pressure of drying chamber is about (20 ÷ 250)mmHg. This system includes drying chamber, piping system, vacuum pump and automatic control programme. It is a fairly common drying system, which is widely used in the manufacturing industry [2].

Low-temperature vacuum drying is carried out in condition as follows: the temperature of drying chamber is about (0 ÷ 55)°C, pressure of drying chamber is about (0 ÷ 20)mmHg, this latter method is usually occurs in the third stage of freeze drying. In recent years, scientists have been looking for the appropriate and effective procedure for preserving post-harvest agricultural products. Therefore, the low temperature vacuum drying model will be developed to meet the needs of the food industry. Because energy cost per kilogram of product in the low temperature vacuum drying compared with freeze drying is reduced about (25-35)%, the cost of this drying system is only half compared with the freeze drying system, so it can be applied to the actual productive situation in Vietnam [2-3]. In addition, to evaluate the quality of the low - temperature vacuum drying system have been made, it used the carrot material (*Daucus carota L*) to test in this study. The purpose of this experiment is to check the quality of the low – temperature vacuum drying system, how good vacuum drying method is and is it as advantageous as expected?

Carrots play a very important role in providing β -carotene to the human body. Beside, carrot is one of the popular root vegetables grown throughout the world and become the essential source of dietary nutrients (*Table 1 and 2*). Carrots contain not only a lot of β - carotene but also a lot of minerals and some other chemical composition, it is very good healthy for

human. However, carrot nutrition be easily decomposed if it is not suitable preserved, [4-5]. Therefore, the problem posed here is how to determine technology mode of low – temperature vacuum drying in order to preserve them in a long time after harvesting for using and commercial. All of this will be answered in the results of this study.

Table 1. *Macroelement components of carrot (The ratio of initial material weight, %), [4]*

Component	Value
Water	88.8
Protein	0.7
Lipid	0.5
Carbohydrate	6.0
Total sugars	5.6
Crude fiber	2.4

Table 2. *Microelement components of carrot (The ratio of initial material weight, mg/100g) [4]*

Component	Value	Component	Value
Ca	34		
Fe	0.4	Zn	0.2
P	25.0	β -carotene	5.33
Na	40.0	Thiamin	0.04
K	240	Riboflavin	0.02
Mg	9.0	Niacin	0.2
Cu	0.02	Vitamin C	4.0

2. MATERIALS AND METHODS

2.1. Tools and equipment

To perform this study, some of the following equipment are needed, [5-6]:

- Mass Determination Device (Sartorius Digital Calculator, made in Canada, error 0.01): determine moisture content.
- HPLC equipment: analyze β -carotene content
- Wattmeter tool: determine energy costs.

- The others (lathes, milling, welding, pipe bending and polishing machine): fabricate this drying system.

2.2. Methods of calculation, design and manufacture

In order to calculate and design this low-temperature vacuum drying system, several methods have been used [7-8]:

- Calculation of material balance.
- Calculation of energy balance.
- Calculation of force balance.
- The use of Autocad software to design.
- The use of information technology for programmable controller.

- The use of precision mechanical methods to construct.
- Other supports from mathematical tools.

2.3. Experimental method to evaluate the quality of the low temperature vacuum drying system [9]

Carrots are dried in different technological modes on the low temperature vacuum drying system. Results obtained will evaluate the energy consumption of 1 kg, the residual water content of final product, and the loss of beta-carotene content, reversibility of the product as well as evaluate quality of the low temperature vacuum drying system.

3. RESULTS AND DISCUSSION

3.1. Theory diagram of the low - temperature vacuum drying system

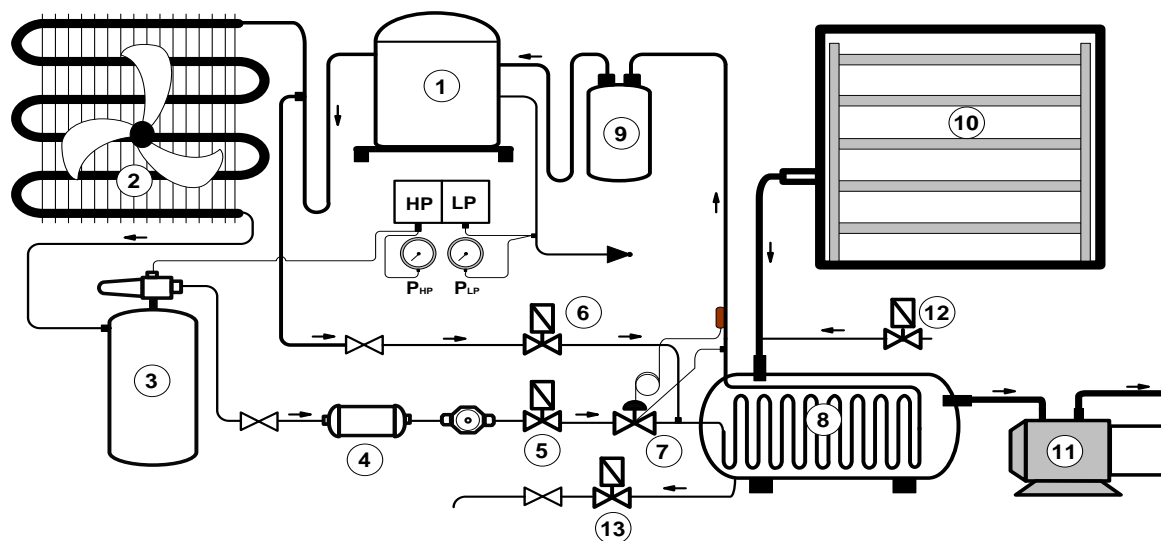


Figure 1. Low temperature vacuum drying system

1. Compressor, 2. Condenser, 3. Receiver tank, 4. Filter, 5. Liquid solenoid valve, 6. Defrost solenoid valve, 7. Throttle - valve, 8. Gas-water separator, 9. Suction accumulator, 10. Drying chamber, 11. Vacuum pump, 12. Vacuum discharge solenoid valve, 13. Water discharge solenoid valve.
 HP. High pressure relay, LP. Low pressure relay.

It can be seen this drying system is very complex, so the calculation and design process of the low temperature vacuum drying system is not simple [10].

3.2. Calculation and design

3.2.1. The initial parameters [10]

- Productivity: $G = 5.3 \text{ kg/batch}$

- Initial sample moisture content: 88.8%
- Final sample moisture content: 5%
- Density of sample: $\rho = 1035 \text{ kg/m}^3$
- Temperature of drying chamber: 40°C .
- Vacuum pressure of drying chamber: 2 mmHg

- The drying time of batch: 18h.
- Atmosphere parameters in Ho Chi Minh City: $t = 30\text{ }^{\circ}\text{C}$; $\varphi = 74\%$; $t_u = 25\text{ }^{\circ}\text{C}$; $t_s = 23\text{ }^{\circ}\text{C}$; $d \approx 0,0202\text{ kg/kg}$ dried air; $h = 81,76\text{ kJ/kg}$ dried air.

3.2.2. Calculation and design of drying chamber [10]

The drying chamber capacity is determined by equation (1) as follows:

$$V = \frac{G}{\rho}, \text{ m}^3/\text{batch} \quad (1)$$

Where, V (m^3/batch): the drying chamber capacity; G (kg/batch): drying chamber productivity; ρ (kg/m^3): density of carrots

From equation (1) and after calculating, the drying chamber size is 450 mm x 420 mm x 525 mm.

Its shape is rectangular and consist of 5 heat transfer plates, 10 drying trays. The inside bulkhead is constituted by stainless steel 304 with its thickness of 4 mm whereas the outside bulkhead is made from stainless steel 201 mm with its thickness of 2 mm. These two bulkheads is separated by a polyurethane foam layer with its depth of 40 mm and 6 force bearing made from stainless steel 201.

3.2.3. Calculate energy balance and mass balance of the low temperature vacuum drying system [8-10]

- Energy for heating up materials was determined by equation (2) as follows:

$$Q_1 = G \times c_g \times (t_2 - t_1) / \tau_n, \text{ KJ} \quad (2)$$

$$= 0.009 \text{ kW}$$

Where, m (kg): material weight of carrot; $c_g = 3.87\text{ kJ}/(\text{kg.K})$: specific heat capacity of material; $t_1 = 30\text{ }^{\circ}\text{C}$: original temperature of material; $t_2 = 40\text{ }^{\circ}\text{C}$: drying temperature; τ_n (s): time of heating up material, $\tau_n = 5760\text{ s}$

- Energy of the drying chamber was lost by haet radiation

$$Q_2 = \varepsilon F_1 c_o \left[\left(\frac{T}{100} \right)^4 - \left(\frac{T'}{100} \right)^4 \right] \quad (3)$$

$$= 0,0215 \text{ KW}$$

Where, F_1 : surface area of the drying chamber (m^2), $F_1 \approx 1,35\text{m}^2$; $\varepsilon = 0.24$: the radiation coefficient; $C_o = 5.67$: the radiative coefficient of the absolute black things; $T = 313\text{K}$; $T' = 303\text{K}$.

- Energy for heating up mechanical equipment in the drying chamber

$$Q_3 = m_{\text{inox}} \times c_{\text{inox}} \times (t_2 - t_1) / \tau_n \quad (4)$$

$$= 0.3 \text{ kW}$$

Where, $m_{\text{inox}} = 350\text{ kg}$: the total mass of inox in the drying chamber; $c_{\text{inox}} = 0.48\text{ kJ}/(\text{kg.K})$ specific heat capacity of inox; τ_n (s): time of heating up material as well as mechanical equipment in the drying chamber.

- Loss of heat throughout the bulkhead Q_{41} and door chamber Q_{42}

$$Q_4 = Q_{41} + Q_{42} \quad (5)$$

$$\approx 0.016 \text{ KW.}$$

Where, λ_1 : the thermal conductivity coefficient of stainless steel ($\lambda_1 = 16\text{W}/(\text{m.K})$), λ_2 : the thermal conductivity coefficient of polyurethane foam layer ($\lambda_2 = 0.047\text{ W}/(\text{m.K})$); $F_{41} = 0.882\text{m}^2$; $F_{42} = 0.473\text{m}^2$

$$Q_{41} = \frac{F_{51}(t_2 - t_1)}{\frac{\delta_1}{\lambda_1} + \frac{\delta_2}{\lambda_2}} = 10.36 \text{ W} \quad (6)$$

$$Q_{42} = \frac{F_{52}(t_2 - t_1)}{\frac{\delta_1}{\lambda_1} + \frac{\delta_2}{\lambda_2}} = 5.56 \text{ W} \quad (7)$$

- Energy for boiling and evaporating water in material

The amount of water released during evaporation was determined by equation (8) as follows:

$$m_1 = G \frac{w_1 - w_2}{1 - w_2} \approx 4.68\text{kg}/\text{batch} \quad (8)$$

Energy for boiling and evaporating water in material was calculated by equation (9)

$$Q_5 = m_1 \cdot r \quad (9)$$

$$= 0.18 \text{ kW}$$

Where, $r = 2409.24\text{ kJ/kg}$: the latent heat of evaporation of water

Total heat load of the low – temperature vacuum drying chamber was determined by equation (10) as follows:

$$Q = k(Q_1 + Q_2 + Q_3 + Q_4 + Q_5) \quad (10)$$

$$= 1200 \text{ W} = 1.2 \text{ kW}$$

Selecting the heating element for dryer: resistor bars. There are 05 heat transfer plates and each plate with 240 Watt.

3.2.4 Calculate for the vacuum pump selection [9-10]

Evacuated capacity of vacuum pump was calculated by equation (11) as follows:

$$Q_b = \beta_1 \beta_2 \cdot \frac{V}{\tau_d} \ln \left[\frac{B - P_{gh}}{P_{bck} - P_{gh}} \right] \quad (11)$$

$$Q_b = 8.94 \text{ m}^3/\text{h}$$

Where, V (m^3): the volume of vacuum chamber; τ_d (h): the expiration time ($\tau_d = 5$ minutes); $B = 760$ mmHg; $P_{\text{limited}} = 0.001$ mmHg: the limited suction pressure of vacuum pump; $P_{\text{vacuum pump}} = 2$ mmHg: the working pressure; $\beta_1 = (1.12 \div 1.5)$: the leakage coefficient; $\beta_2 = (1.12 \div 1.5)$: the safety coefficient.

Therefore, pump capacity was also determined by equation (12):

$$N = \beta \frac{\Delta P_b \cdot Q_b}{1000 \cdot \eta_H \cdot \eta_v \cdot \eta_{ck}} = 731 \text{ W} \quad (12)$$

Where: $\Delta P_b = 2.4 \times 10^5 \text{ N/m}^2$: the pressure formed by vacuum pump, $\eta_H = 0.98$: the hydraulic efficiency, $\eta_v = 0.98$: the volume efficiency, $\eta_{vc} = 0.98$: the mechanical efficiency of vacuum pump, $\beta = (1.12 \div 1.5)$: the safety coefficient of vacuum pump.

Selecting the vacuum pump with $N = 0.75$ kW (1 Hp).

3.2.5. Calculate for the condensing – freezing equipment [8-9]

Initial temperature of moisture: $t_w = t_3 = 40^\circ\text{C}$;

Temperature to be cooled: $t_f = t_1' = -15^\circ\text{C}$;

Chamber moisture content $\phi_1 \approx 5\%$;

The physical parameters of water: $\lambda_1 = 58.4 \times 10^{-2} \text{ W/(m.K)}$; $\beta_1 = 0.98 \times 10^{-4} \text{ K}^{-1}$; $v_1 = 1.23 \times 10^{-6} \text{ m}^2/\text{s}$; $Pr_1 = 8.895$

$$Gr_1 = \frac{g \cdot \beta_1 \cdot d^3 \cdot \Delta t}{v_1^2} = 34893.27 \sqrt[3]{\frac{2 \cdot k_{ld} \cdot V_{ngdb}}{\pi}}$$

$$Ra_1 = (Gr.Pr)_1 = 34395.4$$

$$500 < Ra_1 < 2 \times 10^7$$

$$Nu_1 = C \times Ra_1^n = 7.38$$

Heat transfer coefficient of environment:

$$\alpha_1 = Nu_1 \frac{\lambda_1}{d} = 431 \text{ W/(m}^2 \cdot \text{K)} \quad (13)$$

Total heat load of the condensing – freezing equipment was determined by equation (14):

$$Q_0 = Q = G \Delta h = G(h_3 - h_1') \quad (14)$$

$$= 611.8 \text{ W}$$

Assume heat exchange efficiency $\eta = 70\%$. Therefore, $Q_0 = 874 \text{ W}$

Heat transfer coefficient of the equipment was calculated by equation (15):

$$K = \frac{1}{\frac{1}{\alpha_1} + \frac{1}{\alpha_2} + \frac{\delta_w}{\lambda_w}} = 65 \text{ W/(m}^2 \cdot \text{K)} \quad (15)$$

Heat transfer surface area of the equipment was calculated by equation (16):

$$F = \frac{Q_0}{K \cdot \Delta t} \approx 0.28 \text{ m}^2 \quad (16)$$

The gas water separator is designed in cylindrical form, the diameter is D_{ng} (m), length is L (m), with $L = 2D_{ng}$ and the fill up coefficient is $k_{ld} = 2.0$. For this reason, the capacity of the device is determined by equation (17) as follows:

$$V_{ngdb} = \frac{\pi D_{ng}^2}{4} L = \frac{\pi D_{ng}^3}{2} = k_{ld} \cdot V_{ng} \quad (17)$$

$$\approx 0.007 \text{ m}^3$$

$$D_{ng} = \sqrt[3]{\frac{2 \cdot k_{ld} \cdot V_{ngdb}}{\pi}} \approx 0.17 \text{ m} \quad (18)$$

It can be chosen: $D_{ng} = 0.2 \text{ m}$

$$L_{ng} = 2.5 \times D_{ng} = 0.5 \text{ m}$$

Total copper pipes was also determined by equation (19) as follows:

$$n = \frac{F_{ngdb}}{\pi \cdot l' \cdot d_{ngdb}} = 20 \text{ pipes} \quad (19)$$

3.2.6. Calculated the refrigeration system of condensing – freezing equipment [8-10]

Refrigerant: R22 is chosen.

The boiling temperature of the refrigerant at the evaporator: $t_o = -20^\circ\text{C}$, evaporating pressure $P_o = 2,455$ bar

Condensation temperature of the refrigerant: $t_k = 40^\circ\text{C}$, condensing pressure $P_k = 15,315$ bar

Compressive ratio:

$$\beta = \frac{P_k}{P_o} < 9 \quad (20)$$

As a result, 1 level compressed air is chosen in this system.

The subcooling temperature of the refrigerant after leaving the gas – water separator: $t_{\text{subcooling}} = 35^\circ\text{C}$

The superheat temperature of the refrigerant vapor from the evaporator before the compressor suits: $t_{\text{superheat}} = -15^\circ\text{C}$.

Specific heat rejection capacity $q_k = h_2 - h_3 \approx 166$ kJ/kg

Table 3a. State parameters at specific points of refrigeration cycle

Point	t_o ($^\circ\text{C}$)	P (bar)
1	- 20	2.455
1'	- 15	2.964
2	-	15.268
3	40	15.268
3'	35	15.268
4	- 20	2.455

Table 3b. State parameters at specific points of refrigeration cycle

Point	h (kJ/kg)	v (m^3/kg)	s (kJ/kg.K)
1	397.07	0.09293	-
1'	399.16	0.07769	1.7741
2	415.19	-	1.7741
3	249.22	-	-
3'	176.34	-	-
4	176.34	-	-

- **Calculate for selecting refrigeration compressor**

Directive capacity of refrigeration compressor was determined by equation (21)

$$N_i = \frac{N_s}{\eta_i} = 91 \text{ W} \quad (21)$$

Friction capacity of refrigeration compressor was determined by equation (22)

$$N_{ms} = V_{tt} \cdot P_{ms} = 20.2 \text{ W} \quad (22)$$

Useful capacity of refrigeration compressor was determined by equation (23)

$$N_e = N_{ms} + N_i = 111.2 \text{ W} \quad (23)$$

Power capacity of refrigeration compressor was determined by equation (24):

$$N_{el} = \frac{N_e}{\eta_{td} \cdot \eta_{el}} = 0.2 \text{ KW} \quad (24)$$

Installed motor capacity of refrigeration compressor was determined by equation (25):

$$N_{dc} = 1.25 \times N_{el} = 250 \text{ W} \quad (25)$$

Therefore, the compressor which has its electrical power of 0.5 Hp is selected.

- **Calculate for the condensing equipment**

Heat released at the condensing equipment:

$$Q_k = m q_k = 0.66 \text{ kW} \quad (26)$$

Required temperature of the air to cool the output t_{w2} and input t_{w1} is 38°C and 30°C , respectively. Condensation temperature of the refrigerant: $t_k = 40^\circ\text{C}$.

Heat exchanger area of the condensing equipment was determined by equation (27):

$$F = \frac{Q_k}{k \cdot \Delta t_{tb}} \approx 1.2 \text{ m}^2 \quad (27)$$

Where, K ($\text{W}/(\text{m}^2 \cdot \text{K})$): heat transfer coefficient; Q_k (W): thermal load of the condenser; Δt_{tb} : the average temperature difference between the refrigerant and cooling environment.

The condensing equipment which has its capacity of 0.25 Hp is chosen.

- **Calculate expansive valve**

Refrigerant: R22.

Cooling capacity: $Q_o = 874W$

Evaporation temperature $t_o = -20\text{ }^\circ\text{C}$;

Condensation temperature $t_k = 40\text{ }^\circ\text{C}$;

The pressure difference across the expansive valve: $\Delta p = p_k - p_o - \Delta p_{do} = 12.313\text{bar}$

Where, Δp_{do} : loss of pressure on the pipe (about 0.5 bar); p_k : condensation pressure; p_o : evaporation pressure.

For this reason, the expansive valve chosen to use in this refrigeration system was EV-50. It was very suitable cooling capacity.

3.3. Manufacturing of the low-temperature vacuum drying system

From calculating data, the low temperature vacuum drying system was made at B108 room, HCMC University of Technology and Education.



Figure 2. Low-temperature vacuum drying system

In Figure 2, it can see that this vacuum drying system was automatically controlled by IoT (Internet of Things).

3.4. Checking the quality of the low-temperature vacuum drying system

Putting trays contained carrot sample on heat transfer plates in the drying chamber of the low temperature vacuum drying system.



Figure 3. Carrot products after drying

Experiments are performed at technological mode as follows: the temperature of drying chamber is $49\text{ }^\circ\text{C}$; pressure of drying chamber is 0.01 mmHg; time of drying process is 13 hours. The results of product after drying obtained as follows: the residual water content of product is 3.78%; the energy consumption of 1 kg product is 3.56 kWh/kg product; the loss of total β -caroten inside carrot is 3.96%; the rehydration capacity of product (recovery yield) is 98.2% and other sensory characteristics unchanged.

Obviously, the value of product is beyond expectations, other sensory properties stay remained, the residual water content of product is below 5% in order to prolong the preservation time. The energy consumption of 3.56 kWh/kg product as well as the loss of β -carotene under 5% are reasonable. All of this outstanding benefits has once again proved the quality of low temperature vacuum drying system.

4. CONCLUSION

This research has developed the low temperature vacuum drying system with stable quality. This method replaces the sublimation method for post-harvest preservation and brings benefits to the agricultural economy in Vietnam. The food produced from this drying system has given favorable structure, met the standard of the residual water content of drying product, reduced the loss of quality of product, diminished the energy cost. As a trend of food industries nowadays, it should be applied in

food process and preservation to consolidate the quantity of food for the world.

The low - temperature vacuum drying system connected to IoT technology in automatically monitoring and controlling has reduced the number of labors, total production costs and keep up with the tendency of 4.0 technology.

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