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Optimization of a Combined Heat Pump–Microwave Drying Process of Tilapia Fillets Using a Comprehensive Weighted Scoring Method

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Abstract

Tilapia fillets were dried with combined method of heat pump drying followed by microwave drying in heat pump drying temperature (30, 35 and 40°C), moisture content at the transition point of drying stages (30, 40 and 50%), and microwave drying power (119, 252 and 385 W). The regression model for the comprehensive weighted scores of the drying energy consumption and the product rehydration rate at various weights as a function of heat pump drying temperature, moisture content at the transition point of drying stages, and microwave drying power and its corresponding optimized process parameters were obtained. The analysis of process parameter data optimized at different weight levels of the drying energy consumption and the product rehydration rate indicates that, when the ratio of weight of the drying energy consumption over weight of the product rehydration rate increases, the optimized value of the heat pump drying temperature rises slightly but the rise is insignificant, whereas the optimized value of the moisture content at the transition point of the combined drying processes and that of microwave drying power increase.

Keywords: Tilapia fillet; combined heat pump–microwave drying; Response Surface Analysis (RSA); Comprehensive weighted scoring method

Introduction

The tilapia farming industry has developed rapidly in China, which has become the biggest tilapia farming country in the world with annual output of 1.21 million tons in 2007 increased from 18,000 tons in 1984, accounting for 45% of the world annual output [1]. The moisture content of fish is as high as 5 kg/kg (db) on average, and with moisture content as high as 80% (wb), tilapias are very perishable foods [1,2]. Upto now, the main processed tilapia products are frozen whole rounds and frozen fillets. Processing methods are simple but the processed quantity is only 6.2% of the total tilapia output; therefore, it is worthwhile to investigate the tilapia processing issue.

Drying is regarded as a common technology used in preservation and processing of agricultural and marine products [3]. Drying methods are roughly divided into three major types, heating, osmotic dehydration and chemical extraction of moisture [4]. The hot-air drying belongs to heat drying, quite a few researchers are dedicated to its study, and it is more common in actual production [5,6]. Hot-air drying is the most frequently used method for food drying treatment, but prolonged hot-air drying and high drying temperature easily lead to problems such as loss of product flavor, poor color, loss of nutrients, reduced product rehydration rate, migration of soluble solute, great energy consumption in processing, etc. [7-11].

Drying methods such as heat pump drying, microwave drying, and combined drying have been widely studied and applied in recent years [12,13]. Compared with hot-air drying, heat pump drying has a wide range of temperatures and can be easily controlled, so that low-temperature drying can be efficiently achieved to preserve the quality of heat-sensitive food with good energy conservation effect [14]. However, compared with microwave drying, the heat pump drying has a longer time and still a temporal accumulation effect on product quality. Compared with hot-air drying, microwave drying is quicker with shorter time, and can preserve product quality well with lower drying energy consumption [15-17]. The heat of microwave drying comes from the internal part of material to be heated, immune to the restriction of Fourier Law; its temperature gradient is in the same direction as moisture gradient, while the direction of heat transfer is the same as that of mass transfer, which can effectively increase the heat diffusion rate and mass diffusion rate, and enables a quick drying rate [18]. Therefore, the application of microwave drying in food drying becomes wider and wider. Albeit, a microwave drying system need high initial investment and operating cost, it is not economic to take microwave heat as the sole energy, especially for high-moisture-content materials with long constant-speed drying stage; microwave drying is more suitable to dry low-moisture-content products with low convection heat transfer efficiency [10,19]. To overcome the economical limit of microwave drying, a combined drying method can be adopted. Combined drying is a sort of hybrid drying technique that combines two or more drying methods running in stages or simultaneously to take advantage of and complement each method, so as to avoid the disadvantages of any single drying method (e.g., low drying efficiency and poor product quality) and to retain the product quality to the maximum extent and save energy consumption [18-20,21]. Since microwave drying is more suitable to dry low-moisture-content food, a combined multistage drying mode (hot-air drying or heat pump drying, followed by microwave drying) is more widely applied.

In this study we adopted a combined multistage drying mode (heat pump drying followed by microwave drying) to dry tilapia fillets [10],

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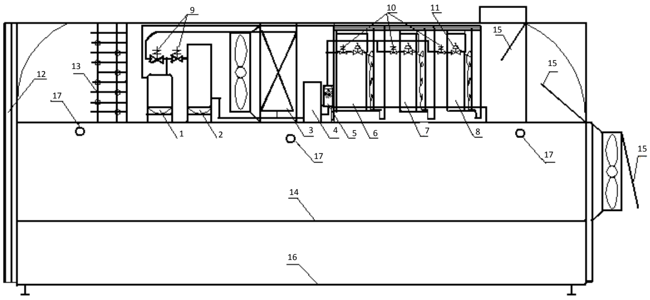

Figure 1: Schematic diagram of the heat pump drying system.
1—Compressor set. 2—Water-cooled tube condenser. 3—Air-cooled fin condenser. 4—Fluid reservoir. 5—Drying filter. 6—The first evaporator. 7—The second evaporator. 8—The third evaporator. 9—Air-discharging valve. 10—Fluid-feeding valve. 11—Thermal expansion valve. 12—System door. 13—Additional electric heating device. 14—Air flow valve. 15—Adjustable valve. 16—Tunnel. 17—Temperature–humidity probe.

conducted experiments with heat pump drying temperature, moisture content at the transition point of drying stages, and microwave drying power as influential factors, and drying energy consumption (DEC) and product rehydration rate (PRR) as experimental indices; calculated their comprehensive weighted scores at different weights of experimental indices; and employed response surface analysis (RSA) to obtain a regression model for the above experimental indices at different weights; optimized three process parameters, i.e., heat pump drying temperature, moisture content at the transition point of drying stages, and microwave drying power; and studied the law of the optimized values of these process parameters varying with experimental indices at different weights, so as to balance between reducing drying energy consumption and increasing product rehydration rate at different weights of experimental indices, and thus to provide a useful reference for the application of combined heat pump-microwave multistage tilapia fillet drying technology.

Experimental Equipment and Process Methods

Apparatus and equipment

We used a self-built heat pump drying system, as shown in figure 1. This system has a drying temperature range of 20–80°C, a drying air velocity range of 0.1–3 m/s, and a drying capacity of 1,500 g±200 g fish, a Midea™ MK823ESJ-PA microwave oven, Guangdong Midea Group Co., Ltd.; a JA2003 electronic balance, Shanghai Huyueming Scientific Instruments Co., Ltd.; an HHS-21-4 thermostatic water bath boiler, Hangzhou Hui'er Instrument & Equipment Co., Ltd.; and a 210 mm desiccator.

Process flow

Select fresh tilapias with uniform size, and remove their scales, guts, heads, and tails; clean well; and slice fish directly from the backbone, one fillet on each side. Fillet size is as per one-dimensional model, and controlled at sizes of about 110×90×4 mm. After filleting, remove the skin, then sterilize the fillets in flowing ozone solution with a concentration of 11 mg/L for 10 min. Decant and set to dry, take samples to measure the initial wet-basis moisture content (78%). For subsequent drying test, weigh 1500 g±2 g fish fillets per batch, and run three parallel experiments. In this study, the drying of tilapia fillets is broken down into two stages, heat pump drying and microwave drying. During heat pump drying stage, the moisture content of tilapia fillets falls from the initial one (78%, wb) to the moisture content at the transition point of combined drying stages. During microwave drying stage, the moisture content of tilapia fillets falls from the one at the transition point of combined drying stages to the one at drying endpoint (15%, wb). Every 30 min (heat pump drying stage) or 2 min (microwave drying stage) in drying process, remove tilapia fillets from heat pump drier or microwave drier, and place onto electronic balance to weigh, then calculate the moisture content at this time. The time of each weighing must not be more than 10 s.

Determination Methods

Determination of moisture content

The direct drying method in Chinese Standard GB 5009.3-2010 is adopted: Tilapia fillets are put in a 105°C thermostatic oven for drying till constant mass and then weighed to yield the dry-matter mass of tilapia fillet. The wet-basis moisture content (W_m) is calculated as follows:

$$W_m = \frac{M_w}{M_d + M_w} \times 100\%, \quad (1)$$

where M_w is the mass of tilapia fillet moisture in grams and M_d is the mass of tilapia fillet dry matter in grams.

Determination of product rehydration rate

The preliminary experiment indicates that product rehydration rate does not basically change after rehydrating for more than 40 min, so we chose 40 min as the rehydration time. Use filter paper to blot up the surface moisture of the rehydrated product repeatedly, and then weigh its mass. The determination procedure is as follows: Weigh dried tilapia fillet (M_1), put into 40°C thermostatic water bath boiler, rehydrate (40 min), take out and filter dry, remove surface moisture, and weigh the mass (M_2); the calculation formula for product rehydration rate (PRR) is

$$\text{PRR} = \frac{M_2 - M_1}{M_2} \times 100\%. \quad (2)$$

Determination of energy consumption

The power supply for the heat pump drying system and the microwave drying chamber is connected to a single-phase kWh meter, which records readings before and after the experiment; the difference between the two readings is the drying energy consumed (DEC) in the experiment.

Determination of comprehensive weighted score

The lower the drying energy consumed during drying, the better the production benefit; the higher the product rehydration rate of the dried fillet, the better the product quality. In this study, drying energy consumption (DEC) and product rehydration rate (PRR) serve as experimental indices, and according to their weights, the test results of double indices are converted to test results of one index, i.e., comprehensive weighted score. In practical production, the weight of each experimental index is determined by importance and degree of attention of it. When different weights are set for experimental indices, calculate the comprehensive weighted scores respectively.

The two indices, DEC and PRR, are nondimensionalized as follows:

$$\text{DEC:}\ Y_1^{'} = \frac{(1/Y_1 - 1/Y_{1\max})}{(1/Y_{1\min} - 1/Y_{1\max})} \times 100, \quad (3)$$

$$\text{PRR:}\ Y_2^{'} = \frac{Y_2 - Y_{2\min}}{Y_{2\max} - Y_{2\min}} \times 100, \quad (4)$$

and the comprehensive weighted score is

$$Y = \lambda_1 Y_1^{'} + \lambda_2 Y_2^{'} \quad (5)$$

where, Y is comprehensive weighted score of test result for a factor mix; Y_1' and Y_2' are nondimensionalized values of measured drying energy consumption and product rehydration rate for a factor mix respectively; λ_1 and λ_2 are weights of drying energy consumption and product rehydration rate respectively; Y_1, $Y_{1\max}$ and $Y_{1\min}$ are measured value of drying energy consumption for a factor mix, the maximum and minimum of measured drying energy consumption values for all factor mixes, respectively; Y_2, $Y_{2\max}$ and $Y_{2\min}$ are measured value of product rehydration rate for a factor mix, the maximum and minimum of measured product rehydration rate values for all factor mixes, respectively.

Statistic data analysis

Excel 2000 is used to analyze and plot the data. The response surface analysis (RSA) and the analysis of variance (ANOVA) are done by using Design Expert 7.0 statistical analysis software. A value of $P<0.05$ represents a significant level.

Results and Discussion

Preliminary experiment

There are many factors influencing the characteristics and quality of combined heat pump–microwave drying of tilapia fillets, mainly including the heat pump drying temperature, the velocity of heat pump drying medium (air velocity), the microwave drying power, the microwave drying time, and the moisture content at the transition point of drying stages, Previously, this task group has done preliminary experiment for combined heat pump–microwave drying of tilapia fillets [22], which reveals that:

(1) In the first heat pump drying stage, the heat pump drying air velocity was set at 3.0 m/s in order to increase the first-stage drying rate while guaranteeing quality of dried products, and low-temperature drying method was employed by setting the heat pump drying temperature to 35°C which acts as the zero level of independent variable for combinatorial design of experiments, so as to prevent the tilapia fillet from producing conditions such as losses of flavors and nutrients, brown color, decreased bulk density and reduced product rehydration, rate caused by prolonged high-temperature drying [8].

(2) In the second microwave drying stage, it is advised to adopt a wait-and-heat drying method. When the microwave drying power is 252 W, one waiting interval is 1 min, and one drying interval is 1 min, the dried fillets are tough and retain the characteristic taste and mouthful of the fish; as the drying interval extends to 1.5 min or 2.0 min, the product gradually hardens, loses the characteristic freshness of the fish, and turns yellowish. Consequently, in this study we defined a microwave drying interval of 1 min, and one waiting interval of 1 min, and selected a post microwave drying power of 252 W as zero level of independent variable of the combinatorial design of experiments.

(3) When tilapia fillets are dried to 40% (wb) moisture content by means of heat pump drying, the drying rate gets smaller gradually due to reduced efficiency of convection heat transfer; thus, the moisture content at the transition point of drying stages is set at 40% (wb) as the zero level of independent variable of combinatorial design of experiments.

Factor coding table

On the basis of our preliminary experiment, with drying energy consumption (DEC) and product rehydration rate (PRR) as experimental indices, and the comprehensive weighted score Y for experimental indices at variable weights as response value; and with three factors, namely, heat pump drying temperature (X_1), moisture content at the transition point of drying stages (X_2), and microwave drying power (X_3), as independent variables; we employed Design Expert software to design a three-factor, three-level response surface optimization experiment, in order to seek the relationship between the comprehensive weighted value of tilapia fillet DEC and PRR and the three selected independent variable factors, and to find its regression model, so as to further optimize the parameters of the combined drying process. The results of our preliminary experiment are taken as the zero levels of the independent variable factors, and the experimental factor-level coding table is shown in Table 1.

Variable	Factor	Level		
		−1	0	1
X_1	Heat pump drying temperature [°C]	30	35	40
X_2	Moisture content at the transition point of drying stages [%]	30	40	50
X_3	Microwave drying power [W]	119	252	385

Table 1: Factor-level coding table.

Test No.	Test matrix			DEC (Y_1) [kWh]	PRR (Y_2) [%]	Comprehensive weighted score (Y)
	X_1	X_2	X_3			
1	−1	−1	0	15.7	53.9	38.6
2	+1	−1	0	13.4	46.6	39.8
3	−1	+1	0	12.2	39.9	37.0
4	+1	+1	0	15.5	47.3	26.8
5	−1	0	−1	12.2	49.0	54.9
6	+1	0	−1	11.3	51.1	68.3
7	−1	0	+1	12.5	39.7	33.9
8	+1	0	+1	11.0	34.2	38.6
9	0	0	−1	14.1	55.5	52.0
10	0	+1	−1	12.2	47.0	51.0
11	0	−1	+1	13.2	52.1	52.2
12	0	+1	+1	14.0	43.6	29.4
13	0	0	0	10.5	59.7	94.7
14	0	0	0	10.5	53.2	81.9
15	0	0	0	11.0	51.3	72.1
16	0	0	0	10.1	56.0	92.7
17	0	0	0	11.0	59.0	87.2

Table 2: RSA (Response Surface Analysis) experimental scheme and results (λ_1 =0.5, λ_2 =0.5).

RSA and Process Parameter Optimization When Setting Weights of DEC and PRR at 0.5 Each

RSA Scheme and regression model

We designed a three-factor, three-level RSA experiment which consists of 17 test points, by setting weights of DEC and PRR as λ_1 =0.5, λ_2 =0.5, and taking the comprehensive weighted score of DEC and PRR as response value. The experimental scheme and results are shown in table 2. Test Nos. 13–17 are center-point tests whereas the others are non-center-point tests; center-point test is repeated five times and is used to estimate the experimental error.

Based on the results given in table 2, we used Design Expert 7.0 statistical analysis software to run multivariate regression analysis and found that the influence of every specific experimental factor on the response value is not simply linear. After performing a regression fitting, we found that the influence of experimental factor on response value can be expressed by the following regression equation:

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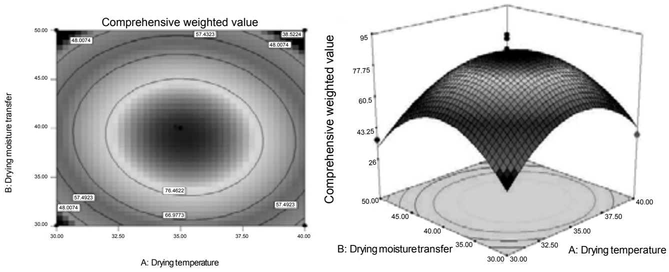

Figure 2: Influence of heat pump temperature–transition moisture content interaction on comprehensive weighted index value(λ_1=0.5, λ_2=0.5).

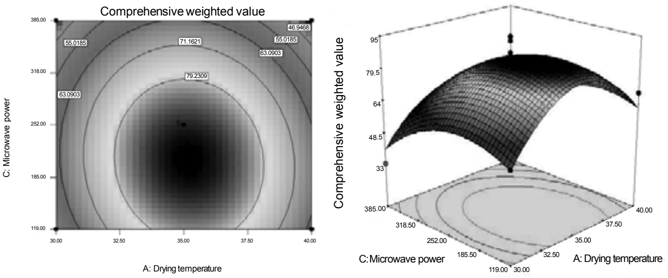

Figure 3: Influence of heat pump temperature–microwave power interaction on comprehensive weighted index value(λ_1=0.5, λ_2=0.5).

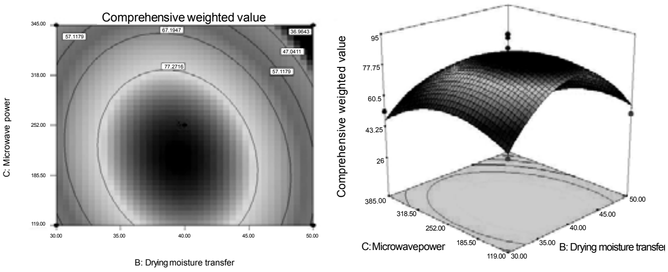

Figure 4: Influence of microwave power–transition moisture content interaction on comprehensive weighted index value(λ_1=0.5, λ_2=0.5).

$$Y = 85.72 + 1.16X_1 - 4.80X_2 - 8.99X_3 - 2.85X_1X_2 - 2.13X_1X_3 - 5.45X_2X_3 - 23.67X_1^2 - 26.50X_2^2 - 13.07X_3^2. \quad (6)$$

The RSA diagrams and isoline diagrams of the comprehensive weighted scores based on the regression equation are given in (Figures 2-4), which comprehensively reflect the influences of factor interactions on the comprehensive weighted score. As found from the figures, every factor interaction has some impact on the comprehensive weighted score. When the heat pump temperature is 35°C or so, the comprehensive weighted score reaches a maximum. When the heat pump temperature is constant, the comprehensive weighted score rises first and then falls with the increase in transition-point moisture content and in microwave drying power.

ANOVA of Quadratic Response Surface Regression Model

As shown in Table 3, the ANOVA of the comprehensive weighted score model shows that the linear term (X_3) and the quadratic terms (X_1^2, X_2^2, X_3^2) have significant (P<0.05) or very significant (P<0.01) impact on the experimental indices, whereas the other terms have insignificant (P>0.05) impact. Eliminating the insignificant terms yields the model equation

$$Y = 85.72 - 8.99X_3 - 23.67X_1^2 - 26.50X_2^2 - 13.07X_3^2. \quad (7)$$

The coefficient of determination of the regression model, R^2, is 0.9342, indicating that the model regressiveness is very significant and attains a good level. As shown in table 3, it can be obtained from the model lack-of-fit test that the lack-of-fit terms are insignificant (P>0.05). The results of both coefficient of determination and lack-of-fit test indicate that this model fits the actual case well; hence it can be used to analyze and predict the change of comprehensive weighted score as a function of heat pump drying temperature, transition-point moisture content, and microwave drying power.

Validation of regression model

Three additional validation tests beyond RSA experimental scheme were done to determine and verify DEC and PRR, and the comprehensive weighted scores were calculated when weights of DEC and PRR were set to 0.5 each. The simulated values (Y_m) were calculated from the regression model Eq. (7), and compared with the test values (Y_e) of the validation tests (Table 4).

As seen in table 4, all absolute errors between test values of the three validation tests and the corresponding model-predicted values are less than 5%, indicating that the regression model Eq.(7) basically reflects the relationship between comprehensive weighted score and the three selected factors when the weights of combined tilapia fillet DEC and PRR are set to 0.5 each.

Optimization of process parameters

To optimize the process parameters of the combined drying of tilapia fillets, we employed Design Expert 7.0 software to solve for the extremes of the regression model and to give its optimal solution. When the heat pump drying air velocity is 3.0 m/s, the microwave drying interval is 1 min, and the waiting interval is 1 min, and the weights of DEC and PPR are set to 0.5 each, the optimized parameters are as follows: heat pump drying temperature is 35.21°C, moisture content

Source of variance	Sum of squares	Degrees of freedom	Mean square	*F* value	*P* value
X_1	10.81	1	10.81	0.14	0.7195
X_2	184.32	1	184.32	2.38	0.1665
X_3	646.20	1	646.20	8.36	0.0233
X_1X_2	32.49	1	32.49	0.42	0.5375
X_1X_3	18.06	1	18.06	0.23	0.6436
X_2X_3	118.81	1	118.81	1.54	0.2551
X_1^2	2359.53	1	2359.53	30.52	0.0009
X_2^2	2956.28	1	2956.28	38.23	0.0005
X_3^2	719.54	1	719.54	9.31	0.0186
Model	7685.36	9	853.93	11.04	0.0023
Residual	541.24	7	77.32		
Pure error	331.65	4	82.91		
Lack of fit	209.59	3	69.86	0.84	0.5375
Total variation	8226.60	16			

Table 3: ANOVA of comprehensive weighted scores(λ_1=0.5, λ_2=0.5).

Test No.	X_1	X_2	X_3	Test value (Y_e)	Simulated value (Y_m)	Error [%]
1	−1	−0.5	0	29.3	28.4	−3.17
2	0.5	1	0	29.6	30.4	2.70
3	0	0.5	1	28.2	27.5	−2.55

Table 4: Data of regression model validation (λ_1=0.5, λ_2=0.5).

at the transition point of drying stages is 39.42%, microwave drying power is 207.33 W. The maximum estimated value of the comprehensive weighted score is 87.39, when the estimated DEC is 10.63 kWh and the estimated PRR is 56.89%.

Process parameter optimization and change laws when setting DEC and PRR at variable weights

Prpcess parameter optimization when setting DEC and PRR at variable weights: Because DEC and PRR are weighted differently, the coefficient of the comprehensive weighted regression model differs. We conducted RSA and ANOVA on comprehensive weighted scores at variable ratios of (DEC weight)/(PRR weight), eliminated insignificant terms (*P*>0.05), and presented the comprehensive weighted regression models at variable weight ratios and optimized process parameters. Table 5 presents the regression models and their optimized process parameters when setting DEC and PRR at variable weights.

As seen from table 5, for these comprehensive weighted regression models, the coefficient of determination (R^2) at different ratios of (DEC weight)/(PRR weight) is 0.8811–0.9439, indicating that the model regressiveness is significant and attains a good level; and the lack-of-fit test statistic (*P* value) is 0.2759–0.5375, with all lack-of-fit terms being insignificant (*P*>0.05). The results of both coefficient of determination and lack-of-fit test indicate that the models in table 5 fit the actual case well; thus they can be used to analyze and predict the change of comprehensive weighted score as a function of heat pump drying temperature, transition-point moisture content, and microwave drying power.

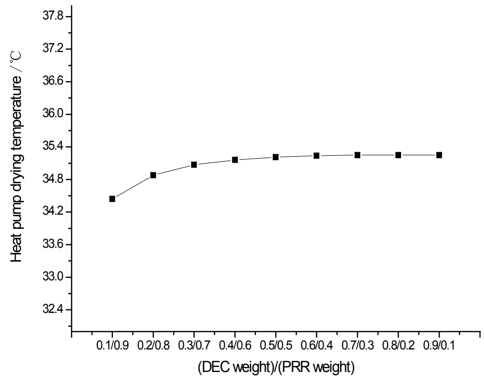

Figure 5: Influence of the (DEC weight)/(PRR weight) ratio on the optimized value of the heat pump drying temperature.

Change laws of optimized process parameters when setting DEC and PRR at variable weights: The determination of DEC weight and PRR weight is limited by many factors including processing, economy and policy, thus balancing their weights is a complicated optimization problem and it is hard to define a uniform standard for it. Therefore, it will be of more universal significance to study influences of DEC weight and PRR weight on optimized process parameters and their change laws. Since DEC weight and PRR weight are correlated (their sum is equal to 1), it is suitable to characterize the change in both weights with a ratio of (DEC weight)/(PRR weight). Based on the optimized process parameters at different ratios of (DEC weight)/(PRR weight) given in Table 5, we plotted the optimized values of heat pump drying temperature, moisture content at the transition point of drying stages, and microwave drying power against the ratio of (DEC weight)/(PRR weight), as shown in Figures 5-7.

Figure 5 shows that the optimized value of the heat pump drying temperature increases slightly with the increase in the ratio of (DEC weight)/(PRR weight), but the rise is small and insignificant. Figures 6 and 7 indicate that the optimized value of the moisture content at the transition point of drying stages and that of microwave drying power increase with the increase in the ratio of (DEC weight)/(PRR weight).

When the (DEC weight)/(PRR weight) ratio increases, the optimized value of the moisture content at the transition point of drying stages and that of microwave drying power increase accordingly. Such change can be explained as follows: increasing the moisture content at the transition point of drying stages means higher moisture extraction amount, longer drying time and more energy consumption in heat pump drying stage on one hand; and on the other hand, it means reduced moisture extraction amount and energy consumption in microwave drying stage. Since the unit energy consumption of microwave drying is less than that of heat pump drying, the total DEC is raised [17]. Increasing the microwave power can shorten the drying time and reduce energy consumption of microwave drying stage [17] and total DEC. Optimizing process parameters through RSA makes that the reduction in total DEC caused by increasing microwave drying power is greater than the increase in total DEC caused by raising moisture content at the transition point of drying stages, their synergetic effect manifests as reduction in total DEC, i.e., more attention or bigger weight is paid to energy consumption, which is equivalent to an increase in (DEC weight)/(PRR weight) ratio.

When the ratio of (DEC weight)/(PRR weight) decreases, the optimized value of moisture content at the transition point of drying stages and that of microwave power in microwave drying stage fall accordingly. Such change can be explained as follows: reducing moisture

Weight		Comprehensive weighted regression models and their statistic indices			Optimized process parameters		
DEC, Y_m	PRR, λ_2	Comprehensive weighted regression model	Coefficient of determination, R^2	Lack-of-fit test statistic, *P*	Heat pump drying temperature [°C]	Moisture content at transition point of drying stages [%]	Microwave drying power [W]
0.1	0.9	$Y = 85.03 - 12.84X_2 - 14.74X_3 - 28.21X_1^2 - 17.87X_3^2$	0.8811	0.4284	34.44	33.02	202.73
0.2	0.8	$Y = 85.20 - 10.83X_2 - 13.31X_3 - 27.08X_1^2 - 13.95X_2^2 - 16.68X_3^2$	0.8940	0.4665	34.88	36.34	202.52
0.3	0.7	$Y = 85.37 - 11.88X_3\ 25.95X_1^2 - 18.11X_2^2 - 15.50X_3^2$	0.9085	0.5059	35.07	37.92	203.71
0.4	0.6	$Y = 85.54 - 10.45X_3\ 24.82X_1^2 - 22.28X_2^2 - 14.32X_3^2$	0.9226	0.5359	35.16	38.82	205.47
0.5	0.5	$Y = 85.72 - 8.99X_3\ 23.67X_1^2 - 26.50X_2^2 - 13.07X_3^2$	0.9342	0.5375	35.21	39.42	207.38
0.6	0.4	$Y = 85.88 - 7.59X_3\ 22.58X_1^2 - 30.61X_2^2 - 11.95X_3^2$	0.9413	0.4967	35.24	39.83	210.10
0.7	0.3	$Y = 86.05 - 21.42X_1^2 - 34.77X_2^2 - 10.77X_3^2$	0.9439	0.4208	35.25	40.14	213.43
0.8	0.2	$Y = 86.21 - 13.19X_1X_2 - 20.29X_1^2 - 38.94X_2^2 - 9.59X_3^2$	0.9429	0.3398	35.25	40.37	217.30
0.9	0.1	$Y = 86.38 - 16.64X_1X_2 - 19.16X_1^2 - 43.10X_2^2$	0.9394	0.2759	35.25	40.53	222.89

Table 5: Regression models and their optimized process parameters when setting DEC and PRR at variable weights.

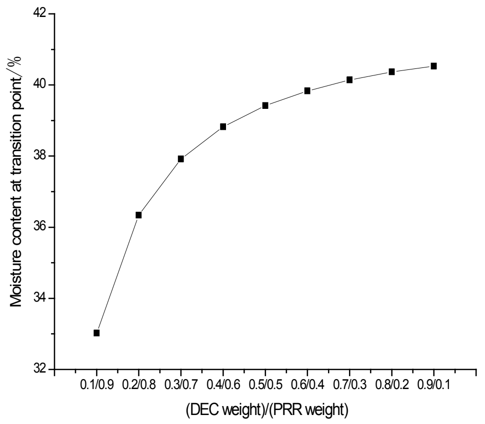

Figure 6: Influence of the (DEC weight)/(PRR weight) ratio on the optimized value of the moisture content at the transition point.

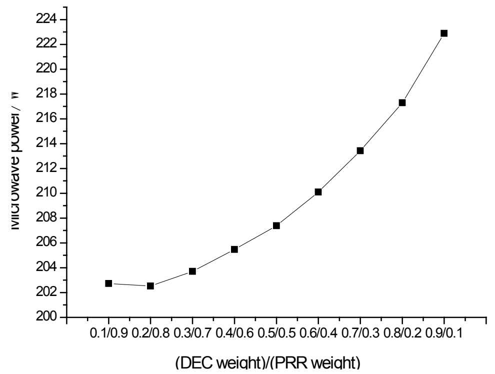

Figure 7: Influence of the (DEC weight)/(PRR weight) ratio on the optimized value of the microwave power.

content at the transition point of drying stages means smaller moisture extraction amount and shortened drying time in heat pump drying stage, which mitigates the influence of long drying time on product rehydration rate [8]; reducing moisture content at the transition point of drying stages means an increase in moisture extraction amount in microwave drying stage, and since the product rehydration rate of a microwave-dried product is higher than that of a heat pump-dried product, microwave drying can improve product rehydration rate [23], and increasing moisture extraction amount in microwave drying stage facilitates improvement in product rehydration rate. Therefore, if the moisture content at the transition point of drying stages is decreased, then both drying stages can improve the product rehydration rate; this superposed effect will enhance overall product rehydration rate of the product. The higher the microwave drying power, the greater the product rehydration rate [4], so decreasing microwave power in microwave drying stage will reduce product rehydration rate. Optimize process parameters through RSA so that the reduction in PRR caused by lowing microwave drying power is less than the increase in PRR caused by lowing the moisture content at the transition point of drying stages, and their synergetic effect shall manifest as improvement in PRR, that is, more attention or bigger weight is paid to PRR, which is equivalent to a reduction in the (DEC weight)/(PRR weight) ratio.

Conclusion

1. Presented regression model of comprehensive weighted score of drying energy consumption and product rehydration rate at various weights as a function of the heat pump drying temperature, moisture content at the transition point of drying stages, and microwave drying power.
2. When the heat pump drying air velocity is 3.0 m/s, the microwave drying interval is 1 min, and the waiting interval is 1 min, the optimized process parameters of comprehensive weighted scores at different weights of DEC and PRR in combined heat pump-microwave drying of tilapia fillets are given.
3. The optimized value of the heat pump drying temperature increases slightly with increase in the ratio of (DEC weight)/(PRR weight), but the rise is small and insignificant. The optimized values of moisture content at the transition point of drying stages and that of microwave drying power increase with the increase in the ratio of (DEC weight)/(PRR weight).

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References

1. Li J, Li BS, Li W (2009) Study of tilapia pickling technique. Modern Food Sci Technol. 25: 646-649.
2. Duan, ZH, Yi MH, Wang ZG (2005) Processing technique of tilapia. Fish Sci. Technol Inform. 32: 250-252.
3. Tippayawong N, Tantakitti C, Thavornun S (2008) Energy efficiency improvements in longan drying practice. Energy 33: 1137-1143.
4. Duan ZH, Jiang LN, Wang JI, Yu XY, Wang T (2011) Drying and quality characteristics of tilapia fish fillets dried with hot air-microwave heating. Food Bioprod Process 89: 472-476.
5. Aktas T, Fujii S, Kawano Y, Yamamoto S (2007) Effects of pretreatments of sliced vegetables with trehalose on drying characteristics and quality of dried products. Food Bioprod Process 85: 178-183.
6. Gogus F, Maskan M (2006) Air-drying characteristics of solid waste (pomace) of olive oil processing. J Food Eng 72: 378-382.
7. J Varith, P Dijkanarukkul A, Achariyaviriya S, Achariyaviriya (2007) Combined microwave-hot air drying of peeled longan. J Food Eng 81: 459-468.
8. G Ru′ız D′ıaz, J Mart′ınez-Monzo′, P Fito, A Chiralt (2003) Modelling of dehydration-rehydration of orange slices in combined microwaveyair drying. Innovative Food Science and Emerging Technologies 4: 203-209.
9. Drouzas AE, Tsami E, Saravacos GD (1999) Microwave/vacuum drying of model fruit gels. J Food Eng 39: 117-122.
10. Maskan M (2001) Drying, shrinkage and rehydration characteristics of kiwifruits during hot air and microwave drying. J Food Eng 48: 177-182.
11. Sharma GP, Prasad S (2001) Drying of garlic (Allium sativum) cloves by microwave-hot air combination. J Food Eng 50: 99-105.
12. Figiel A (2010) Drying kinetics and quality of beetroots dehydrated by combination of convective and vacuum-microwave methods. J Food Eng 98: 461-470.
13. Colak N, Hepbasli A (2009) A review of heat-pump drying (HPD): Part 2—Applications and performance assessments. Energy Conserv Manage 50: 2187-2199.
14. Neslihan Colak, Arif Hepbasli (2009) A review of heat pump drying: Part 1—Systems, models and studies. Energy Conver Manage 50: 2180-2186.
15. Dı′az, GR, Martı′nez-Monzo′ J, Fito P, Chiralt A (2003) Modelling of dehydration-rehydration of orange slices in combined microwave/air drying. Innovat Food Sci Emerg Tech 4: 203-209.
16. Feng H (2002) Analysis of microwave assisted fluidized-bed drying of particulate product with a simplified heat and mass transfer model. International Communications in Heat and Mass Transfer 29: 1021-1028.

17. Ilknur Alibas (2007) Microwave, air and combined microwave-air-drying parameters of pumpkin slices. LWT 40: 1445-1451.

18. AS Kassem, AZ Shokr, AR El-Mahdy, AM Aboukarima, EY Hamed (2011) Comparison of drying characteristics of Thompson seedless grapes using combined microwave oven and hot air drying. J Saudi Soc For Agric Sci 10: 33-40.

19. Tadeusz Kudra, Arun S. Mujumdar (2002) Advanced Drying Technologies [M]. Translated by Zhanyong Li, Beijing: Chemical Industry Press, 2005: 207.

20. Fatouh M, Metwally MN, Helali AB, Shedid MH (2006) Herbs drying using a heat pump dryer. Energy Conver Manage 47: 2629-2643.

21. Wojdyło A, Figiel A, Oszmianski J (2009) Effect of drying methods with the application of vacuum microwaves on the bioactive compounds, color and antioxidant activity of strawberry fruits. J Agric Food Chem 57: 1337-1343.

22. Guan Zhiqiang, Zheng Lijing , Li Min, Guo Shenglan. (2012) Preliminary Studies on the Combined Drying Technology of Heat Pump with Microwave Drying of *Tilapia* Fillets. Food Sci (in Chinese with English abstract), 33:in press.

23. MAM Khraisheh, WAM McMinn, TRA Magee (2004) Quality and structural changes in starchy foods during microwave and convective drying. Food Res Intl 37: 497-503.