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Quality Optimization in Red Pepper Drying

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Abstract

Optimal drying conditions consisting of air temperature and relative humidity were searched by the simulation-optimization technique for minimizing quality changes in red pepper drying. Optimized drying conditions were analysed in the viewpoint of quality change kinetics and effects of control variables on the state variables. Optimal drying conditions were nearly same in both cases for carotenoid maximization and browning minimization. In two staged optimized drying, relative humidity took a lower search limit of about 10%, and air temperature in the first stage was near the lower limit of 50 °C and in second stage increased to a higher temperature varying with total drying time and stage changing time. Response surface analysis of time invariable drying confirmed the location of the optimal point lying on the vertex of lower limit humidity and a lowest drying temperature which ensures to attain target moisture of 0.2g water/g dry solid. Two stage drying can attain the higher objective function of quality by 3-5% than time invariable drying for shorter total drying times.

Key words: optimization, red pepper drying, quality, carotenoids, browning

Introduction

Quality of dried red pepper depends on the drying conditions such as drying method and drying temperature. Quality losses in red pepper drying are caused by carotenoid destruction and nonenzymatic browning(1-3). Proper sun drying was reported to produce good quality of red pepper(1,3). But it takes long time to sun-dry the red pepper and some of red pepper is decayed during long period of drying(4). Recently hot air dryer has been widely used to dry large amount of red pepper in short time. In hot air drying, drying conditions greatly affect the quality of red pepper. Generally the drying below 70 °C is recommended for better quality(4,5). Low temperature drying requires long drying time and therefore restricts the output of the dryer. More elaborate scheme of the drying conditions can be useful for the improvement of the dried red pepper quality and dryer efficiency. For finding optimal conditions the simulation optimization method is an efficient tool which saves expensive experimentaion and time. Various optimization techniques were successfully applied in the food dehydration problems(6-7). We used mathematical optimization techniques to search for the optimal drying conditions of red pepper which minimize the deleterious quality changes in drying.

Materials and Methods

The simulation model of red pepper drying was established from data and models of the literatures. The established model was then used for the simulation and the optimization by linking to pertinent iterative scheme.

Drying model

Drying model of Cho *et al.*(8) was adopted and used for simulation of the moisture removal during drying. This model was derived by Cho *et al.*(8) from linking of Lewis's model to diffusion model of drying. The rate of moisture decrease is given as equation (1).

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$$\frac{dm}{dt} = -\left(\frac{0.50201}{60}\right)\exp\left(\frac{-186.51}{T_{db}}\right)(100m - 100m_e)^{(0.5384-0.002585RH)} \quad (1)$$

In equation (1) equilibrium moisture content is given by Henderson equation (2).

$$m_e = \frac{\left(\frac{\ln(1-RH/100)}{-1.2188\times10^{-3}(T_{db}+2.576)}\right)^{1.0088}}{100} \quad (2)$$

The experimental conditions of Cho *et al.*(8) cover the drying temperature of 50-80 °C and relative humidity of 10-70%.

Change of food temperature during drying

A heat balance on the food was used to determine the food temperature.

$$\frac{dT_s}{dt} = \frac{hA}{m_sC_p}(T_{db}-T_s) - \frac{\lambda}{C_p}\left(\frac{dm}{dt}\right) \quad (3)$$

Through the drying, h and A change because of shrinkage and other effects. In our study hA/m_s was curvefitted as a function of moisture content from experimental data T_{db}, T_s, dm/dt and dT_s/dt obtained by Cho *et al.*(8) The relation is as follows;

$$\frac{hA}{m_s} = 3436.7 + 2840.6m - 577.5m^2 \quad (4)$$

Model of quality change

Carotenoid destruction and nonenzymatic browning were considered in the quality optimization of red pepper drying. Models of Lee *et al.*(9) were used for the optimization.

Carotenoid destruction is known to follow the first order kinetics when O_2 is not restricted. The rate could be expressed as a function of moisture and temperature as following;

$$\frac{dC}{dt} = -kC \quad (5)$$

$$k = k_o\exp(-E_{ac}/RT_s) \quad (6)$$

$$\ln k_o = 4.1879 - 1.9466m + 3.2619m^2 \quad (7)$$

$$E_{ac} = 7698.3 - 692.58m + 1911.2m^2 \quad (8)$$

Nonenzymatic browning is usually expressed as a zero order reaction. Rate of browning is given as follows:

$$\frac{dB}{dt} = k_b \quad (9)$$

$$k_b = k_{bo}\exp(-E_{ab}/RT_s) \quad (10)$$

$$\ln k_{bo} = 1.6492 + 5.5260m + 0.1713m^2 \quad (11)$$

$$E_{ab} = 7459.2 + 3736.5m + 2.9828m^2 \quad (12)$$

For the simulation of state variables in red pepper drying, the differential equations (1), (3), (5) and (9) must be solved. In our study Runge-Kutta's method was used by linking to IMSL routine DVERK (IMSL, Inc., Houston).

Optimization

As seen in equation (1), the red pepper drying process depends on the drying air temperature and relative humidity. Therefore these two variable were chosen as the control variables for the optimization of the objective function of carotenoid retention or browning. At first, two stage drying of red pepper was to be optimized in these control variables. Method of Umeda *et al.*(10) was modified, which utilizes complex method of multivariable constrained optimization as an optimization algorithm for continous variables. The control variables were assumed to change stepwise. As independent variables the control variables of two stages and the step changing time were numerically searched by Box's complex method to minimize quality change in the drying. In order to remove the discontinuities of control variables between stages the control variables were to take the linearly interpolated values during the stage change of 20 minutes. This procedure can be summarized in Fig. 1. Initial moisture, food temperature, carotenoid concentration and browning level were assumed to be 3.4g water/g dry solid, 25 °C, 370 mg/100 g dry solid and 0.027 (O.D. at 420 nm), respectively. The search ranges were 50-80 °C of air temperature and 10-70% of relative humidity, respectively(8).

In analysing the effect of control variables in optimization response surface analysis was adopted. The state variables of moisture, carotenoid retention and browning were simulated for the combinations of control variables in time invari-

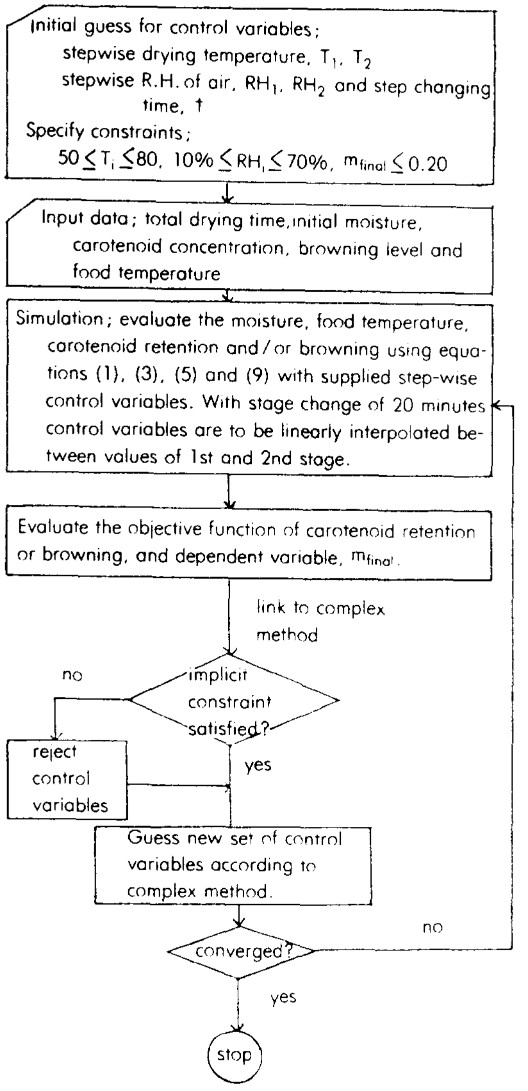

Fig. 1. Algorithm of quality optimization in red pepper drying.

able drying according to central composite design. These results were used for the determination of the parameters of equation (13) by nonlinear regression, and contour maps were constructed. Park's[11] computer program SNURSA was used.

$$Y=\beta_o+\sum_{i=1}^{2}\beta_i u_i+\sum_{j\geq i}^{2}\beta_{ij}u_i u_j \qquad (13)$$

The air temperature was also searched which attain target moisture 0.2g water/g dry solid under relative humidity of 10% for specific total drying time. Fibonacci search technique[12] was used for this purpose by minimizing the difference between final moisture and the value 0.20. All the computation was done by Televideo TS 2605 personal computer.

Results and Discussion

Optimal profiles of air temperature and relative humidity in two stage drying

The searched pattern of two stage drying of red pepper for maximum carotenoid retention is presented in Fig. 2 for the total drying time of 12 hours. The optimal pattern of control variables consists of initial low temperature drying around 51 °C and latter high temperature drying of about 69 °C both under low humidity of 11%. These profiles attribute to the carotenoid destruction kinetics in red pepper drying. Carotenoid destruction rate constant has a high value at high moisture content, decreases to a minimum value with moisture decrease and then increases a little with further moisture removal to complete dryness[9]. Humidity at low limit might be used for the acceleration of moisture removal. For carotenoid retention air temperature keeps near the low limit of 50 °C when the moisture of red pepper being dried is high. The drying temperature takes a higher

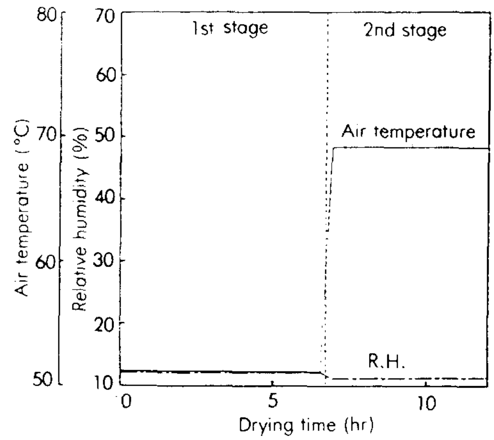

Fig. 2. Optimal control variables for the carotenoid retention in red pepper drying (total drying time: 12 hours).

value in order to satisfy moisture constraint in given total drying time at the latter stage of drying where carotenoid destruction rate is relatively lower because of low moisture and lower concentration of carotenoids.

Optimal profiles for other total drying times showed similar patterns with specific step changing times, which used lower limit temperatures of around 50 °C at the first stage and higher temperatures at the second stage both with about 10% humidity. The step changing time and the second stage temperature varied with total drying time. In the search, there seemed to exist several local optima of the combinations of these two independent variables of second stage temperature and step changing time with the same low limit humidity and first stage temperature. There were not significant differences among the objective functions of these local optima and general trend of control variables profile was as in Fig. 2. Three staged drying was also tried in optimization, but improved the objective function little. Optimization for browning minimization, another quality factor, was also undertaken. The searched profiles of control variables were compared with those in optimization for carotenoid retention. The patterns of profiles minimizing browning were very similar to those in the cases of carotenoid maximization. These seem to be due to the similar dependences of carotenoid destruction and nonenzymatic browning on moisture in red pepper drying(9). Therefore in red pepper drying carotenoid optimization seems to be able to yield browning minimization, thus only the conditions for carotenoid maximization were discussed and analysed further.

The simulated state variables during optimal red pepper drying of Fig. 2 are shown in Fig. 3. Food temperature stays near the air temperature of 51 °C at the first stage and then increases to near the second stage air temperature of 69 °C with passing the step changing time. This comes from the drying characteristics of red pepper, which mainly consist of falling rate period(8,13), i.e. the red pepper attains the temperature near the drying air temperature from the initial stage of drying. Being influenced by the profiles of control variables, moisture decreases steadily in the first stage and more or less sharply in the latter stage. Changes of moisture and food temperature during drying must affect the carotenoid destruction and browning. Carotenoids decreases smoothly in the first stage because of low food temperature, even though the rate constant is high at high moisture. In the second stage of high temperature carotenoid destruction increases a little, but not greatly probably because of the low rate below the moisture 2.0 g water/g solid(9). It should be noted that these changes result from the control variable profiles maximizing carotenoid retention. Quality change of browning would be also explained by the similar dependence of rate on moisture.

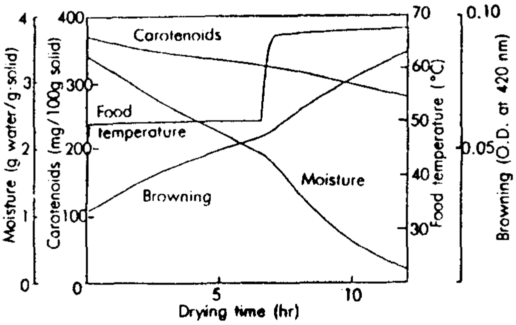

Fig. 3. Simulated state variables in the optimal red pepper drying (total drying time: 12 hours).

Effect of control variables on moisture and quality in red pepper drying

The fact that optimal drying conditions lie on the lower limit humidity of 10% makes it necessary to investigate the dependence of moisture and quality of dried red pepper on the control variables. The surface response analysis was done for this purpose. Contour maps of moisture, carotenoid retention and browning were constructed as functions of time invariable drying air temperature and relative humidity. Fig. 4 shows the con-

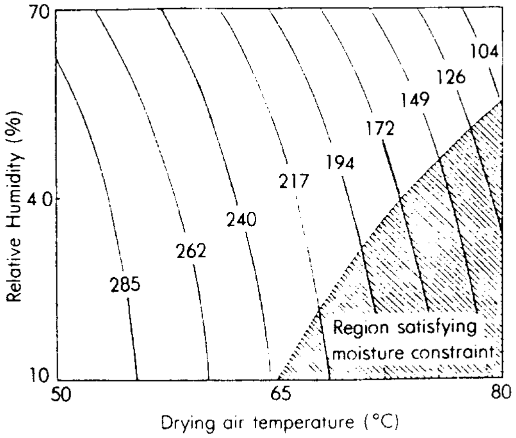

Fig. 4. Contours of carotenoid retention (mg/100g dry solid) in the red pepper drying (total drying time: 12 hours).

tour map of carotenoid retention of 12 hour dried red pepper with satisfying region of moisture constraint. For the moisture removal lower humidity and higher temperature must be combined. Carotenoids are retained more with lower humidity and lower air temperature. In order to attain maximum retention of carotenoids under the moisture constraint of $m \leq 0.20$, air temperature must be as low as possible with lower limit humidity of 10%. In Fig. 4 this optimal point locates on the vertex of 10% R.H. and about 65 °C and produces carotenoid retention of about 239 mg/100g solid. Contours of browning showed similar pattern as those of carotenoid retention and produced the same vertex for browning optimization.

Therefore it is reasoned that optimization of time invariable red pepper drying is the search of the air temperature which attains the moisture 0.2g water/g dry solid under the low limit relative humidity within specified total drying time. This temperature for each total drying time was searched by Fibonacci search technique(12), and presented in Table 1. The optimal drying temperature increases with shorter total drying time. With decrease of total drying time, the optimized carotenoid retention increases up to a maximum and then declines thereafter. Longer total drying time enables lower drying temperature to be used for carotenoid retention but long time exposure even to low temperature reduces the color. Shorter total drying time employs higher temperature and enhances the carotenoids. But with very short total drying time of 9 hours high temperature effect begins to reduce the carotenoid retention. Therefore it is reasoned that there exists optimum drying temperature in red pepper drying, which in turn determines optimum total drying time under given conditions. These results conform to those of Lease *et al.*[5] and Kim *et al.*[13] which showed that there exists optimum temperature around 60 °C for color retention in red pepper drying. The differences of optimal drying temperature and carotenoid retention between Fig. 4 and Table 1 seem to come from the errors of nonlinear regression in surface response analysis. These errors can be reduced by narrowing the analysis range and Fig. 4 was plotted to show the overall trend of quality change depending on the control variables.

The carotenoid retentions of optimal time invariable drying of red pepper were lower than those of the two stage optimal drying by 3-5% for the total drying times of 9-15 hours. With longer total drying times of lower drying temperature the difference became negligible. Conclusively for quality retention red peper drying must be completed in relatively short total drying time using proper drying air temperature under low humidity. In this case two stage drying can improve the objective function somewhat. The drying condi-

Table 1. Optimum drying air temperatures to reach moisture 0.20g water/g dry solid when red pepper is dried under relative humidity of 10% a)

Total drying time (hr)	Optimum drying air temperature (°C)	Carotenoid retention (mg/100g dry solid)
9	65.8	261.7
12	59.7	267.4
15	55.8	268.0
18	52.9	266.6
21	50.7	264.1

a) initial moisture: 3.4g water/g dry solid
initial carotenoid: 370 mg/100g dry solid

tions of low limit humidity can be attained by the low recycle of air in actual drying and will consume large amount of energy(14). In practical dehydration the product quality and energy consumption are contradictory and must be compromised. This can be done by the proper choice of objective function and constraints in optimization. The optimization of practical red pepper drying is now being studied.

Nomenclature

A : Surface area of food (m^2)
B : Browning level (O.D. at 420 nm)
C : Carotenoid concentration (mg/100g dry solid)
C_{ps} : Heat capacity of dry solid (J/kg.°C)
C_{pw} : Heat capacity of water (J/kg.°C)
C_p : $C_{ps} + mC_{pw}$ (J/kg.°C)
E_{ac} : Activation energy of carotenoid destruction (cal/mol)
E_{ab} : Activation energy of browning (cal/mol)
h : Heat transfer coefficient (J/m^2.°C.min)
k : Rate constant of carotenoid destruction (min^{-1})
k_o : Frequency factor in carotenoid destruction (min^{-1})
k_b : Rate constant of browning (ΔO.D. at 420 nm/min)
k_{bo} : Frequency factor of browning (ΔO.D. at 420 nm/min)
m : Moisture (g water/g dry solid)
m_e : Equilibrium moisture content (g water/g dry solid)
m_s : Dry solid weight (kg)
R : Gas constant, 1.987 cal/mol·k
RH,RH_i : Relative humidity (%)
t : Time (min)
T_{db},T_i : Drying air temperature (°C)
T_s : Food temperature (K or °C)
u_i : Normalized control variables of time invariable drying
Y : Dependent variable in response surface analysis
β_i,β_{ij} : Parametrs of equation (13)
λ : Latent heat of water (J/kg)

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고추건조에 있어서 품질 최적화

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고추건조에 있어서 품질의 최적화를 위한 최적건조공기온도와 상대습도를 수학적 최적화기법에 의하여 찾았다. 얻어진 최적 건조조건을 품질변화 kinetics와 제어변수가 상태변수의 변화에 미치는 영향을 관점에서 분석하였다. Carotenoids의 보존과 갈변억제를 위한 최적 건조조건은 거의 일치하였다. 2단계 건조의 최적조건은 상대습도는 약 10%의 하한값을 취하면서 첫번째 단계 건조에서 50℃의 하한온도를 취하고 두번째 단계 건조에서는 고온으로 증가하였다. 두번째 단계 건조온도와 단계 이동시간은 전체건조 소요시간에 따라 달랐다. 제어변수가 시간에 대해 일정한 경우의 고추건조를 반응표면 분석에 의하여 제어변수의 영향을 살펴볼 때 최적점이 하한의 상대습도에서 목적건조 수분함량 0.2(건물기준)를 얻을 수 있는 가장 낮은 건조온도로 결정됨이 확인되었다. 2단계 건조는 건조 소요시간이 비교적 짧을 때 3-5%의 목적함수 개선의 효과가 있었다.