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An experimental approach to optimize several processing conditions when extruding soybeans

N. Jiang[a], A.Z. Zhang[a], R.Q. Yang[a,b,*], Y.C. Zhang[a]

[a] College of Animal Science and Veterinary Medicine, Heilongjiang Bayi Agricultural University, Daqing 163319, People's Republic of China
[b] School of Agriculture and Biology, Shanghai Jiaotong University, Shanghai 200240, People's Republic of China

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ABSTRACT

In this experiment involving extrusion of soybeans, a quadratic orthogonal rotary combination design was used to investigate effects of key extrusion conditions, such as bore diameter, temperature, moisture and rotation speed on extrusion efficiencies as indicated by trypsin inhibitor, chymotrypsin inhibitor, urease, lectin, protein solubility and protein digestibility *in vitro*. As a result, 6 quadratic regression equations of experimental indices under 4 extrusion conditions were separately established. Taking into account the importance of these indices to the nutritional value of soybeans in animal feeding, we propose a set of comprehensive indices to evaluate extrusion efficiency using a fuzzy comprehensive evaluation method. Based on these comprehensive indices, the optimal extrusion conditions for soybeans as a feedstuff can be determined with a single objective quadratic nonlinear programming method.

1. Introduction

Extrusion is a cooking process utilizing pressure-cooking and heat roasting at controlled temperatures, pressures and durations (Serrano and Agroturia, 1997). It was later modified for production of pet foods, fish feeds, non ruminant feeds, as well as a range of human foods such as snack foods, breakfast cereals and candy. Raw soybeans are fed into the extruder barrel and conveyed to the other end by a rotating screw with heat due to friction, which is up to 40 times faster than at atmospheric pressure. The desired shape of the product is then formed through a restricted die opening which creates pressure.

Extrusion cooking impacts nutritional quality of food and feed mixtures (Cheftel, 1986; Asp and Bjorck, 1989; Camire et al., 1990; Arêas, 1992; Singh et al., 2007). Destruction of secondary compounds, gelatinisation of starch, increases in soluble dietary fiber and reductions of lipid oxidation generally improve the nutritional quality through extrusion of food and feed mixtures. However, Maillard reactions between proteins and sugars generally reduce the nutritional value of the protein, and heat-labile vitamins may be destroyed to some extent. Changes in proteins and the amino acid profile, carbohydrates, fiber, vitamins, minerals and some non-nutrient components of food and feed mixtures depends on raw material characteristics (*e.g.*, composition and particle size) and processing conditions (Mercier, 1977; Fadel et al., 1988; Petres and Czukor, 1989; Andersson and Hedlund, 1990; Petres et al., 1990; Asp et al., 1993; Lasekan et al., 1996; Mahungu et al., 1999; Sriburi and Hill, 2000; Athar et al., 2006).

Abbreviations: CP, crude protein; RSM, response surface methodology.

* Corresponding author at: College of Animal Science and Veterinary Medicine, Heilongjiang Bayi Agricultural University, Daqing 163319, People's Republic of China. Tel.: +86 459 681 9206; fax: +86 459 681 9206.
E-mail address: runqingyang@sjtu.edu.cn (R.Q. Yang).

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Table 1
Codes and levels of factors.

Code x'	Extrusion condition			
	x_1 (mm)	x_2 (°C)	x_3 (%)	x_4 (rpm)
−2	6	70	10	220
−1	8	105	15	250
0	10	140	20	280
1	12	175	25	310
2	14	210	30	340

x', the coded value of extruding condition, x_1, bore diameter, x_2, temperature, x_3, moisture, x_4, rotating speed.

Processing conditions are mainly temperature, feed moisture, screw speed and screw configuration. In order to investigate effects of processing conditions on the nutritional quality of food and feed mixtures, response surface methodology (RSM) has been used to reduce experimental times by use of efficient experimental designs such as the quadratic orthogonal rotary combination design (Bastos et al., 1991; Seibel and Hu, 1994; Vainionpää, 1995; Chang and El-Dash, 2003; Emmanuel Kwasi Asare et al., 2004). However, the RSM can be used to study the response of each processing condition, or their combinations, to determine optimum processing conditions.

Optimum processing conditions are generally chosen by maximization, or minimization, of a single experimental index without simultaneously considering multiple experimental indices. In this study, we establish the regression equations of multiple nutritional indices on processing conditions by using a quadratic orthogonal rotary combination design. With this fuzzy comprehensive evaluation method, a set of comprehensive indices is proposed to assess the importance and association of those experimental indices to the nutritional quality of the product. Finally, we determine optimal extrusion conditions for soybeans by a single objective quadratic nonlinear programming method according to various comprehensive indices of multiple experimental indices.

2. Materials and methods

2.1. Experimental design

A quadratic orthogonal rotary combination design was completed to investigate effects of 4 controllable extrusion factors on extrusion efficiencies. These factors were bore diameter (x_1), temperature (x_2), feed or food moisture level (x_3) and rotation speed (x_4), whose levels are in Table 1. Soybeans came from the Agronomic Experimental Station, Northeast Agriculture University in China and contained 90.0 g/kg water; 402.5 g/kg crude protein (CP), 195.6 g/kg ether extract, 6.6 mg/g lectin, 60.8 mg/g trypsin inhibitor and 39.2 cm g/g chymotrypsin inhibitor. Trypsin inhibitor (y_1), chymotrypsin inhibitor (y_2), urease (y_3), lectin (y_4), protein solubility (y_5) and CP digestibility (y_6) *in vitro* were the experimental indices used to evaluate extrusion efficiency. Trypsin inhibitor was measured with the procedure developed by Smith et al. (1980), chymotrypsin inhibitor by Saini (1989), lectin by Grant and van Driessche (1993), and all other experimental indices were obtained according to the methods of Yang (1993). Table 2 shows the scheme of the orthogonal rotation combination design with 12 replicates, with observations of the experimental index in each combination. The extruder used was a single screw with 3 nodes, where the barrel is sectioned into 4 zones. Rotating speed is 0–1200 rpm, and there was a temperature control meter, ammeter and circle loop automatic system. Temperature was regulated at the second, third and fourth zones of the barrel, whose continuously controlling scope was 0–300 °C. Moisture was regulated by mixing soybeans with water at the ribbon mixer, and productivity was 200–250 kg/h.

2.2. Methods

2.2.1. Optimal regression equations

In quadratic orthogonal rotary combination design, a second-order polynomial equation is employed to describe the function of each experimental index y_i $(i = 1, 2, 3, 4, 5, 6)$ on extrusion conditions x_i $(i = 1, 2, 3, 4)$ as:

$$\hat{y}_i = \beta_0 + \sum_{i=1}^{3} \beta_i x'_i + \sum_{i=1}^{3} \beta_{ii} x'^2_i + \sum_{i=1}^{2} \sum_{j=i+1}^{3} \beta_{ij} x'_i x'_j \quad (1)$$

where $\hat{y}_i$ is the predicted value of experimental index, β_0 is the constant term, β_i s is the linear regression coefficient, β_{ii} s is the quadratic regression coefficient, and β_{ij} s is the interaction regression coefficient. $x'_{i(j)}$ s are the coded values of extrusion condition $x_{i(j)}$, and the relationship between $x'_{i(j)}$ and $x_{i(j)}$ is defined as:

$$x'_{i(j)} = \frac{x - 0.5(a_{i(j)} + b_{i(j)})}{0.25(b_{i(j)} - a_{i(j)})} \quad (2)$$