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Inactivation of anti-nutrients in soybeans via micronisation

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Abstract: The soybean (*Glycine max*) is used as one of the main protein sources in various animal fodders. However, the presence of anti-nutrients significantly reduces the nutritional value of the bean. To solve this problem, the present work is devoted to the inactivation of the anti-nutrients in soybeans by the use of micronisation as a means of thermal treatment. The purpose of the work is to improve the process of soybean micronisation by determining the impact of the process parameters on the soybean's quality and energy performance, namely – the urease activity and specific energy consumption. A multifactor experiment was carried out using an experimental device for the heat treatment of the beans. The influence of the temperature and time of the heat treatment on the level of inactivation of anti-nutrients and the specific energy consumption for beans with different sizes were established. The modes of heat treatment which allow the inactivation of the anti-nutrients in the soybeans to admissible standard values were also defined. The obtained and studied functional dependencies of the quality and energy indices on the technological factors of the soybean micronisation allow one to improve this process and technical means for its implementation in reducing the anti-nutrient content.

Keywords: infrared rays; specific energy consumption; thermal treatment; urease

The soybean has a high protein content of up to 50 percent (Rui et al. 2011). The beans are used as one of the main protein sources in various animal fodders (Garnsworthy and Wiseman 2009; Malcolmson et al. 2019; Sońta and Rekiel 2020). The nutrition per 1 kg of soybean is 1.24–1.51 fodder units (Traksler 2008). However, the presence of some anti-nutrients, such as urease, the Kunitz inhibitor and the Bowman-Birk inhibitor, among others, reduces the nutritional value of the soybeans (Leterme et al. 1988; Irvin 1994; Palacios et al. 2004; Martínez et al. 2013). Due to this, prior to being used, it is necessary to treat the raw soybeans in order to inactivate the anti-nutrients (Qin et al. 1996; Wiriyaumpaiwong et al. 2004; Vagadia et al. 2017).

The most widespread thermal methods used in modern technologies to inactivate the anti-nutrients in soybeans are: heat treatment in a drying apparatus, micronisation, treatment in ther-

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mal chambers, extrusion, moisture-heat treatment (Liener 1962; Traksler 2008).

Research confirms that micronisation is one of the most effective methods used for the inactivation of anti-nutrients in soybeans, this modern technological process entails the thermal treatment of the beans by infrared rays (Fasina et al. 2001; Chervyakov 2005; Ligidov 2007).

The high efficiency of the micronisation method is confirmed by the research in scientific work (Zverev and Sesikashvili 2018). However, this work does not cover the influence of the dimensional characteristics of the soybeans on the outcome indices of the micronisation process. Moreover, the values of the specific energy consumption of the soybean micronisation process are not given, which does not allow one to conduct an energy and economic assessment of the technological process.

Thermal treatment by infrared rays with a wavelength of 1 500–3 500 mm was proven to be effective when treating cereals and leguminous crops (Braginets 1989; Deepa and Hebbar 2016), but there are an insufficient number of studies of the ways to improve the grain quality of cereals and leguminous crops by reducing the quantity of anti-nutrients.

To improve the quality of the soybean, it is necessary to optimise the process of its thermal treatment. Insufficient thermal treatment leads to the incomplete inactivation of the anti-nutrients present in the beans. Overheating, on the other hand, causes changes in the chemical structure of many essential amino-acids which leads to a decrease in the nutritional value (Mengesha 2016). So, the need to determine the functional dependence between the incoming and outgoing parameters of the micronisation process and the choice of its acceptable modes is of paramount importance as both insufficient thermal treatment and overheating can lead to a decrease in the quality of soybean fodders (Dudley-Cash 1999; Friedman and Brandon 2001).

Taking the results of the known research into account, the necessity to determine functional dependencies between the temperatures in the micronisation zone, the time for heating the beans, the bean size characteristics and the inactivation level of the anti-nutrients and the specific energy consumption has appeared (Leeson and Summers 2008).

Thus, the purpose of the research is to improve the process of soybean micronisation by determining the impact of the process parameters on its quality and energy performance, namely the urease activity and specific energy consumption, which will further reduce the energy consumption in obtaining high quality products.

MATERIAL AND METHODS

Materials and equipment. The research was conducted on the "Ustya" variety of soybeans with fractions of 4, 5 and 6 mm (the smallest crosscut size of a bean). The 1 000 seeds weight is 155–160 grams. The moisture of beans before the study was 12–14 percent. The research was conducted using an experimental device for heat treatment of soybeans (Plavynskyi et al. 2010) (Figure 1).

To obtain the even action of the infrared rays from the lamps and reflectors over the whole surface of the soybeans, the experimental device provides movement to the beans over the sloping plane of the base with a forward speed (V) in one layer simultaneously with the rotation of the beans with an angular velocity (ω).

The even movement of the soybeans is provided by adjusting the inclination angle of the base plane β (about 20°), the high roughness of the ceramic surface of the base and the even movement of the rod conveyer. The irradiation source was obtained by using QHT 220-600 linear infrared lamps (quartz halogen thermal emitter) (Lisma, Russia) on TC 16-92 IFMR 675000.010 TC, with the following characteristics: rated voltage – 220 V; rated power – 600 W; colour temperature of the lamps – 2 000 K; and a maximum permissible temperature on the lamp surface during operation – 1 073 K.

The concentration of the infrared rays in the irradiation zone was increased by the reflectors. To determine the temperature in the micronisation zone, a DT-8866 laser pyrometer (CEM, China) was used.

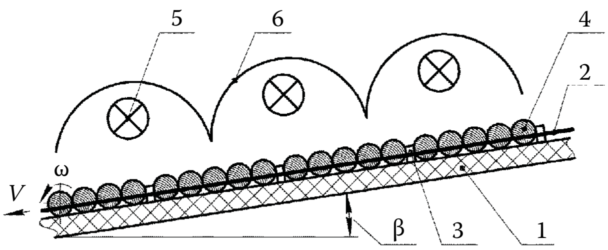

Figure 1. The scheme of the experimental device developed by Plavynskyi et al. (2010)

consisting of the base (1) made of high-temperature ceramics; a rod conveyer (2); rods – decelerators (3); soybeans (4); infrared lamps (5); and reflectors (6)

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A stopwatch with an accuracy class of 0.2 s was used to determine the bean irradiation time.

Methods of research. During the experimental studies into the soybean micronisation process, a non-composite second-order plan was implemented (Spiridonov 1981).

The study (Melcion and Peel 1993) indicates that the quality and energy indices of the soybean micronisation are significantly influenced by different factors, such as the temperature (t, °C) in the micronisation zone and the heating time (T, s).

We have previously established that the dimensional characteristics of the beans (d, mm) also have a significant effect on the quality and energy indices of the micronisation. In order to conduct the experiment, the intervals and levels of variation of the factors to cover the area in which it is advisable to study the technological process was determined (Table 1).

In studying the soybean micronisation process, a non-composite plan of the second order for three factors was implemented (Table 2).

The main advantages of the non-composite plan are:

non-composite plans are more rational than central composite plans of the second order (Spiridonov 1981), these plans appear to be a defined selection of lines from a complete factor experiment of the type 3^k;

in these plans, each variable varies at only three levels: +1, 0, –1, while central composite rotatable plans of the second order provide the usage of each factor at five levels; changing the level complicates the research and increases its cost;

non-composite plans for three factors require fewer experiments compared to the corresponding rotatable central composite plans of the second order.

The effectiveness of the micronization process was evaluated by urease activity in soybeans y_1 and pecific energy consumption y_2.

After each experiment, the soybean samples were cooled, crushed and sifted through a sieve with a mesh of 0.25 millimetres. The urease activity was determined by the standard method of Ukraine – DSTU 8365:2015 (DSTU Ukraine 2015).

The specific energy consumption (Wh·kg^{-1}) in each experiment was determined by dividing the power of the infrared lamps (W) by the performance of the experimental device (kg·h^{-1}).

In order to analyse the results of the study, mathematical models of the micronisation process were used. It further provided an opportunity to present the results of the experiment, both in an analytical and a graphical form.

To describe urease activity in the soybeans (y_1) and the specific energy consumption (y_2), a mathematical model in the form of polynomial of the second degree for three factors was accepted the Equation (1):

$$y = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_{12}x_1x_2 + \\ + b_{13}x_1x_3 + b_{23}x_2x_3 + b_{11}x_1^2 b_{22}x_2^2 + b_{33}x_3^2 \quad (1)$$

where: b_0, b_1, b_2, b_3, b_{12}, b_{13}, b_{23} b_{11}, b_{22}, b_{33} – coefficients of the regression equation; y – value of the outcome parameter; x_1, x_2, x_3 – independent variables, factors of the process.

According to the results of the experiments, conducted in accordance with experimental plan, the coefficients of regression equations were determined using the method of least squares. Subsequently, the statistical processing of the experimental results was performed, regression equations were obtained

Table 1. Variation levels of the factors and their code values

Variation levels of factors	t (°C)	T (s)	d (mm)	Conventional signs	Outgoing parameters: urease activity (ΔpH)	Outgoing parameters: specific energy consumption (Wh·kg^{-1})
Basic level	280	60	5	0	–	–
Variation interval	50	30	1	$\Delta\kappa_i$	–	–
Upper level	330	90	6	+1	–	–
Lower level	230	30	4	-1	–	–
Code value of variables	x_1	x_2	x_3	–	y_1	y_2

x_1, x_2, x_3 – code value of variables; T – time of heating (s); t – temperature (°C); d – bean size (mm); y_1 – urease activity (ΔpH); y_2 – specific energy consumption (Wh·kg^{-1}); $\Delta\kappa_i$ – variation interval the factors x_1, x_2, x_3

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Table 2. The matrix of the non-composite plan of a second order for three factors

No. of experiment	x_0	x_1	x_2	x_3	x_1x_2	x_1x_3	x_2x_3	x_1^2	x_2^2	x_3^2	y_1	y_2
1	+1	+1	+1	0	+1	0	0	+1	+1	0	$y_{1.1}$	$y_{2.1}$
2	+1	+1	−1	0	−1	0	0	+1	+1	0	$y_{1.2}$	$y_{2.2}$
3	+1	−1	+1	0	−1	0	0	+1	+1	0	$y_{1.3}$	$y_{2.3}$
4	+1	−1	−1	0	+1	0	0	+1	+1	0	$y_{1.4}$	$y_{2.4}$
5	+1	0	0	0	0	0	0	0	0	0	$y_{1.5}$	$y_{2.5}$
6	+1	+1	0	+1	0	+1	0	+1	0	+1	$y_{1.6}$	$y_{2.6}$
7	+1	+1	0	−1	0	−1	0	+1	0	+1	$y_{1.7}$	$y_{2.7}$
8	+1	−1	0	+1	0	−1	0	+1	0	+1	$y_{1.8}$	$y_{2.8}$
9	+1	−1	0	−1	0	+1	0	+1	0	+1	$y_{1.9}$	$y_{2.9}$
10	+1	0	0	0	0	0	0	0	0	0	$y_{1.10}$	$y_{2.10}$
11	+1	0	+1	+1	0	0	+1	0	+1	+1	$y_{1.11}$	$y_{2.11}$
12	+1	0	+1	−1	0	0	−1	0	+1	+1	$y_{1.12}$	$y_{2.12}$
13	+1	0	−1	+1	0	0	−1	0	+1	+1	$y_{1.13}$	$y_{2.13}$
14	+1	0	−1	−1	0	0	+1	0	+1	+1	$y_{1.14}$	$y_{2.14}$
15	+1	0	0	0	0	0	0	0	0	0	$y_{1.15}$	$y_{2.15}$

x_1, x_2, x_3 – code value of variables; x_1 – time of heating (s); x_2 – temperature (°C); x_3 – bean size (mm); x_1x_2, x_1x_3, x_2x_3 – multiplication of variables; y_1 – urease activity (ΔpH); y_2 – specific energy consumption (Wh·kg^{-1})

in a decoded form, the graphs of the dependencies were constructed, and their analysis was undertaken.

Statistical processing of the experimental results. To verify the significance of the obtained coefficients of the regression equations, the variance s_y^2 of the experiment's reproducibility by the results of three experiments in the centre of the experiment plan (experiments 5, 10, 15, Table 3) was determined by the Equation (2):

$$s_y^2 = \frac{s_E}{n_0 - 1} = \frac{s_E}{3-1} \tag{2}$$

where: s_E – the sum of the squares of the deviation values which is used to determine of the variance in the experiment's reproducibility according to the results of the experiments in the centre of the plan; n_0 – the number of experiments in the centre of the experiment's plan.

The variances of the regression equation coefficients were determined by the Equations (3–6):

$$s^2\{b_0\} = \frac{1}{n_0} s_y^2 = \frac{1}{3} s_y^2 \tag{3}$$

$$s^2\{b_i\} = A s_y^2 = \frac{1}{8} s_y^2 \tag{4}$$

$$s^2\{b_{il}\} = D s_y^2 = \frac{1}{4} s_y^2 \tag{5}$$

$$s^2\{b_{ii}\} = B_1 s_y^2 = \frac{13}{48} s_y^2 \tag{6}$$

where: A, B_1, D – constants (see Table 3).

The trustworthy intervals of the regression equation coefficients b were determined by the Equations (7–10):

$$\Delta b_0 = \mp t_T\, s\{b_0\} \tag{7}$$

$$\Delta b_i = \mp t_T\, s\{b_i\} \tag{8}$$

$$\Delta b_{il} = \mp t_T\, s\{b_{il}\} \tag{9}$$

$$\Delta b_{ii} = \mp t_T\, s\{b_{ii}\} \tag{10}$$

where: t_T – tabular value of Student's t-test at a 5% significance level for the number of freedom degrees (n_0 – 1).

Table 3. Values of the constants to determine the variances of the regression equation coefficients

Constant	A	B_1	D	n_0
Values	1/8	13/48	1/4	3

A, B_1, D – values of the constants to determine the variances of the regression equation coefficients (Spiridonov 1981); n_0 – the number of experiments in the centre of the experiment's plan

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The significance of the equation coefficients was checked by comparing the absolute value of the coefficients with their trustworthy intervals.

If the calculated value of the equation coefficient for the unknown is less than the absolute value of the corresponding trustworthy interval, then it is considered statistically insignificant and is excluded from the Equation (11).

Condition of the comparison:

$$|b| < \Delta b \qquad (11)$$

The adequacy variance of the obtained model was determined by the Equation (12):

$$s_{ad}^2 = \frac{s_R - s_E}{N - k' - (n_0 - 1)} \qquad (12)$$

where: s_R – the sum of the deviation squares of the empirical values of the response function from its values determined by the model at all points of the plan; s_E – the sum of the squares of the deviation values which is used to determine of the variance in the experiment's reproducibility according to the results of the experiments in the centre of the plan; k' – number of statically significant regression coefficients of the approximating polynomial; n_0 – number of experiments in the centre of the experiment's plan; N – number of experiments in the plan.

After excluding the statistically insignificant coefficients, the obtained mathematical models were checked for adequacy by the *F*-test. The model is considered adequate under the condition:

$$F_p < F_T \qquad (13)$$

where: F_p – the calculated value of the Fisher test; F_T – the tabular value of the Fisher test.

The calculated value of the Fisher test (F_p) was determined by the Equation (14):

$$F_p = \frac{s_{ad}^2}{s_y^2} \qquad (14)$$

where: s_{ad}^2 – the variance of the adequacy.

RESULTS AND DISCUSSION

Mathematical models of the process. The use of infrared rays (micronisation) for the inactivation of anti-nutrients in the soybeans is stipulated by the fact that, in terms of the energy consumption, this process is one of the most effective (Obertukh 2003). One of the most efficient methods of soybean processing to improve their nutritional properties is heat treatment (Lehmali and Jafari 2019); however, this work does not cover functional dependencies be-

Table 4. Results of implementing the experiment-planning matrix

Experiment No.	*t* (°C)	*T* (s)	*d* (mm)	y_1 (ΔpH)	y_2 (Wh·kg^{-1})
1	330	90	5	0.04	100.37
2	330	30	5	0.29	33.46
3	230	90	5	0.21	60.22
4	230	30	5	0.52	20.07
5	280	60	5	0.23	53.53
6	330	60	6	0.18	58.77
7	330	60	4	0.11	78.26
8	230	60	6	0.38	35.26
9	230	60	4	0.36	46.96
10	280	60	5	0.22	53.29
11	280	90	6	0.14	70.52
12	280	90	4	0.11	93.91
13	280	30	6	0.32	23.51
14	280	30	4	0.3	31.30
15	280	60	5	0.24	53.53

t – temperature (°C); *T* – time of heating (s); *d* – bean size (mm); y_1 – urease activity (ΔpH); y_2 – specific energy consumption (Wh·kg^{-1})

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tween the incoming and outgoing parameters of the technological process. As shown in Cai et al. (2021), micronisation is one of the technical interventions, which provides physical modifications of soy products and their improved quality attributes.

As a result of the experiment on the determination of the quality and energy indices of soybean micronisation, the values of the outgoing parameters y_1 and y_2 were obtained (Table 4).

By the results of the experiment, the coefficients of the regression Equations (1) were determined by the method of least squares with the usage of Microsoft Excel. The obtained Equations (15–16) take the following form:

$$y_1 = 0.2300 - 0.1063x_1 - 0.1163x_2 + \\ + 0.0175x_3 + 0.0150x_1x_2 + 0.0125x_1x_3 + \\ + 0.0025x_2x_3 + 0.0375x_1^2 + 0.0025x_2^2 + 0.0100x_3^2 \quad (15)$$

$$y_2 = 53.4511 + 13.5428x_1 + 27.0856x_2 - \\ - 7.7980x_3 + 6.6914x_1x_2 - 1.9495x_1x_3 - \\ - 3.8990x_2x_3 + 0.0403x_1^2 + 0.0403x_2^2 + 1.3194x_3^2 \quad (16)$$

where: y_1 – urease activity (units of ΔpH); y_2 – specific energy consumption (Wh·kg^{-1}); x_1, x_2, x_3 – in a coded form – the temperature in the micronisation zone, the time of soybean staying in the micronisation zone and the dimensional characteristics of bean cross-cut, respectively.

The variances of the experiment's reproducibility, the variances of the regression equation coefficients and their trustworthy intervals were determined by Equations (2–10), and their calculated values are given in Table 5. The significance of the regression coefficients was checked under condition [Equation (11)] by comparing their absolute values with their corresponding trustworthy intervals (Table 5).

According to the test results, the insignificant coefficients at x_1x_2, x_1x_3, x_2x_3, x_2^2, x_3^2 were excluded from Equation (15). The coefficients at x_1^2, x_2^2 were also excluded from Equation (16).

After excluding the insignificant coefficients, the Equations (17–18) took the form:

$$y_1 = 0.2300 - 0.1063x_1 - 0.1163x_2 + \\ + 0.0175x_3 + 0.0375x_1^2 \quad (17)$$

$$y_2 = 53.4511 + 13.5428x_1 + 27.0856x_2 - \\ - 7.7980x_3 + 6.6914x_1x_2 - 1.9495x_1x_3 - \\ - 3.8990x_2x_3 + 1.3194x_3^2 \quad (18)$$

Fisher's test is used to test the models for adequacy. The outgoing data for the calculations are given in Table 6.

Analysing the values in Table 6 under condition Equation (13), we come to conclusion that models Equation (17) and Equation (18) are adequate at a 5% significance level.

Table 5. The values of the experiment's reproducibility variances, the variances of the regression equation coefficients and their trustworthy intervals

Outgoing parameter	Variance of experiment reproducibility (sy_2)	Sum of squares of values deviation in the centre of the plan (s_E)	Variances of regression equation coefficients ($s^2\{b\}$)		Trustworthy intervals of regression equation coeff Δb_x	
			symbol	value	symbol	value
Urease activity (y_1)	0.0001	0.0002	$s^2\{b_0\}$	3.33×10^{-5}	$s^2\{b_0\}$	0.0248
			$s^2\{b_i\}$	−1.25×10^{-5}	$s^2\{b_i\}$	0.0152
			$s^2\{b_{il}\}$	2.50×10^{-5}	$s^2\{b_{il}\}$	0.0215
			$s^2\{b_{ii}\}$	2.71×10^{-5}	$s^2\{b_{ii}\}$	0.0224
Specific energy consumption (y_2)	0.0192	0.0384	$s^2\{b_0\}$	0.0064	$s^2\{b_0\}$	0.3440
			$s^2\{b_i\}$	0.0024	$s^2\{b_i\}$	0.2107
			$s^2\{b_{il}\}$	0.0048	$s^2\{b_{il}\}$	0.2979
			$s^2\{b_{ii}\}$	0.0052	$s^2\{b_{ii}\}$	0.3101

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The transition from the coded values of the variables to the natural ones was carried out according to the Equation (19):

$$x_1 = \frac{t-280}{50}; x_2 = \frac{T-60}{30}; x_3 = \frac{d-5}{1} \tag{19}$$

After replacing the coded values of factors x_1, x_2, x_3 by their natural values (t, T, d) in Equations (17–18), they form Equations (20–21):

$$y_1 = 2.1460 - 0.0105t - 0.0039T + \\ +0.0175d + 0.000015t^2 \tag{20}$$

$$y_2 = -23.2168 + 0.1981t + 0.3036T - \\ -2.2766d + 0.0045tT - 0.0390td - \\ -0.1300Td + 1.3194d^2 \tag{21}$$

where: y_1– urease activity (units ΔpH); y_2– specific energy consumption (Wh·kg^{-1}); t – temperature in the micronisation zone (°C); T – time the soybeans have remaining in the micronisation zone (s); d – size characteristics of the bean cross-cut (mm).

Graphs and their analysis. For a visual reflection, the results of the research are presented in the form of graphs (Figures 2–6).

According to the results of the experiment, the urease activity, at a constant temperature of 280 °C in the micronisation zone, varies according to the linear law and takes values from 0.09 units to 0.32 units (Figure 2). To ensure high quality products (ΔpH = 0.02–0.2 units) for the micronisation of the beans with a size from 4 mm to 6 mm, the following conditions must be met: t = 280 °C; T > 73 seconds.

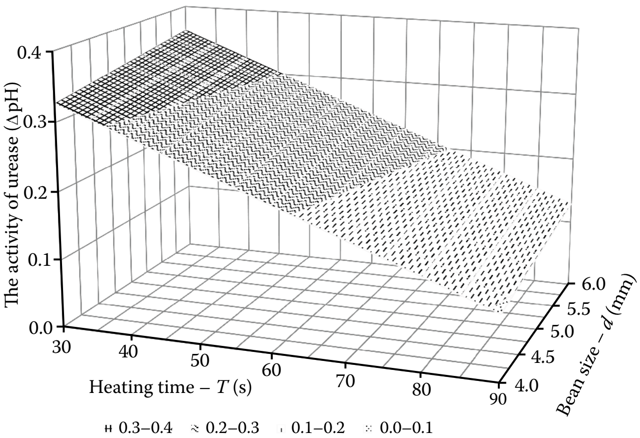

Figure 2. Dependence of the urease activity ΔpH (y_1) on the micronisation time (T) and bean size (d) at a constant temperature (t = 280 °C)

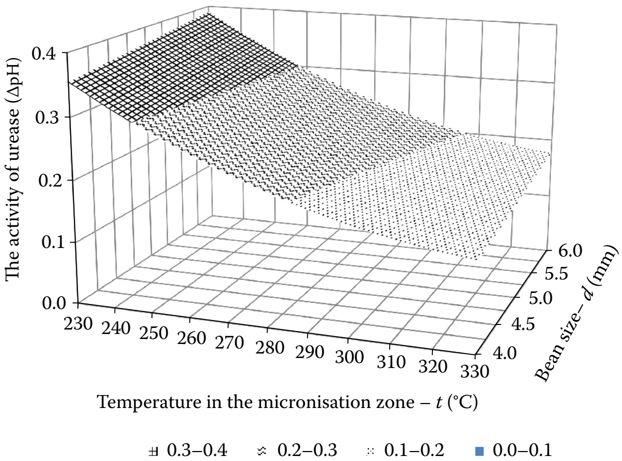

Figure 4. Dependence of the urease activity ΔpH (y_1) on the temperature (t) in the micronisation zone and the bean size (d) at a constant micronisation time (T = 60 s)

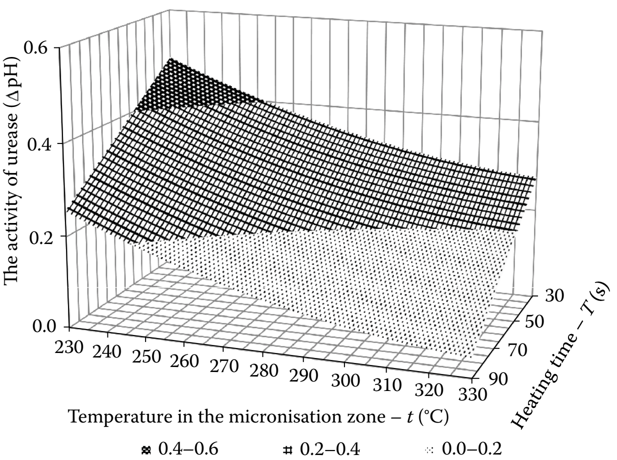

Figure 3. Dependence of the urease activity ΔpH (y_1) on the micronisation time (T) and temperature (t) in the micronisation zone when the bean size is d = 5 millimetres

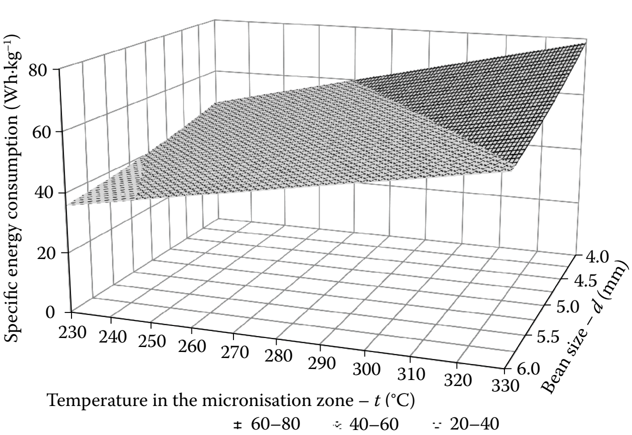

Figure 5. Dependence of the specific energy consumption (y_2) on the temperature (t) in the micronisation zone and bean size (d) at a constant micronisation time (T = 60 s)

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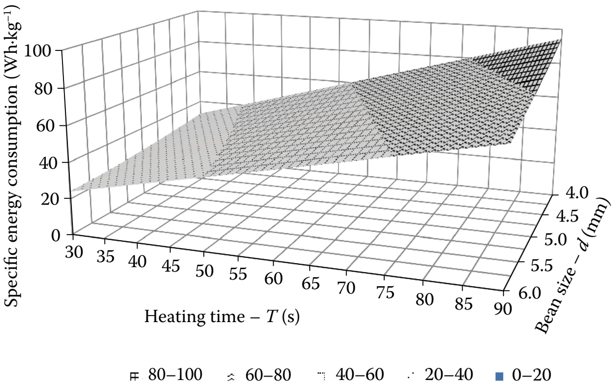

Figure 6. Dependence of the specific energy consumption (y_2) on the micronisation time (T) and bean size (d) at a constant temperature (t = 280 °C).

Table 6. Parameters used to test the models for adequacy by the F-criterion

Outgoing parameter	N	k'	n_0	s_{ad}^2	F_p	F_T (5%)
Urease activity (y_1)	15	5	3	9.5×10^{-4}	9.53	19.3
Specific energy consumption (y_2)	15	8	3	0.2124	11.063	19.3

N – number of experiments in the plan; k' – number of statically significant regression coefficients of the approximating polynomial; n_0 – number of experiments in the centre of the experiment's plan; s_{ad} – the variance of the adequacy; F_p – the calculated value of the Fisher test; F_T – the tabular value of the Fisher test

The dependence of the urease activity on the temperature and the time of micronisation, at a constant bean size (calibrated fraction of 5 mm), is presented in Figure 3. The dependence is non-linear due to an increase in the amount of supplied heat energy with the decrease in the urease activity in the soybeans with an increasing temperature and heat treatment time. For beans with a size of 5 mm, the decrease in the urease activity reaching acceptable values is possible under the condition: t = 330 °C, T > 50 s, or t > 247 °C, T = 90 seconds.

The given graph (Figure 3) provides the opportunity to choose the modes of the micronisation process for the soybeans with a size of 5 mm to provide admissible qualitative indicators of the processing.

A graphic interpretation of the dependence of the micronisation temperature and bean size influence on the level of anti-nutrient inactivation in the soybeans is given in Figure 4.

The dependence is non-linear. At constant micronisation time of (T = 60 s) under condition t > 286 °C for a bean size of 4 mm or t > 308 °C for a bean size of 6 mm, the value of the micronisation quality indicator ΔpH stays within admissible limits, respectively, from 0.2 to 0.14 and from 0.2 to 0.18. The functional dependence of the specific energy consumption (Wh·kg^{-1}) on the temperature in the micronisation zone and bean size at a constant micronisation time of (T = 60 s) has a non-linear character (Figure 5).

During the micronisation of beans of a larger size, the specific energy consumption decreases. This is explained by the efficiency improvement of the experimental device when treating beans of larger size.

Figure 6 shows the dependence of the specific energy consumption on the micronisation time (T) and the bean size (d) at a constant temperature. The dependence is non-linear. With an increase in the heat treatment time of the bean, the specific energy consumption also increases, which is caused by the increase in the energy consumption for the process.

The summary of the research results – the dependence on the most influential factors has been determined for the quality and energy indices of the technological process of soybean micronisation. It was found that the inactivation of anti-nutrients in soybeans of 4, 5 and 6 mm to acceptable standards values (ΔpH = 0.02–0.20) is possible under the following conditions:

d = 4 mm, t = 330 °C, T > 45 s or t > 241 °C, T = 90 s;
d = 5 mm, t = 330 °C, T > 50 s or t > 247 °C, T = 90 s;
d = 6 mm, t = 330 °C, T > 55 s, or t > 252 °C, T = 90 s.

The specific energy consumption for these conditions is within the limits from 53 to 76 Wh per kilogram.

The definition of the functional dependence between the influential technological factors of the soybean micronisation (temperature and time of heat treatment, size of beans) and the qualitative and energetic parameters of the technological process, in particular, the level of anti-nutrient inactivation and specific energy consumption, is new in the process of our research. In this case, with the increasing micronisation temperature, the content of the anti-nutrients decreases, which is confirmed in the studies of other authors (Chen 2015; Zverev et al. 2018). A decrease in the urease activity with an increasing micronisation temperature is also observed at different values of the soybean moisture (White

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et al. 2000; Yalçın and Basman 2015; Zverev and Sesikashvili 2018; Morgunova et al. 2020), although the influence of the humidity on the micronisation process was not taken into account in our studies.

The high efficiency of the micronisation is ensured by the fact that the soybeans were moving with constant even rotation in the heat treatment zone. At the same time, the even heating of the beans and, accordingly, the even inactivation and exclusion of the point overheating of the beans are taking place. A similar bean rotation technology is used in other studies (Zilic et al. 2012), where beans are moved by a vibrating conveyor.

The expediency of determining the energy consumption when using infrared rays has also been confirmed by other researchers (Avilés-Gaxiola et al. 2018). In addition, the assessment of the energy consumption in Wh·kg^{-1} allows one to determine productivity of the technological process and its economic efficiency.

The obtained functional dependencies provide the opportunity to set up the parameters of the technological process for the soybean micronisation with the previously given qualitative and energy indices.

At constant temperature values (t = 280 °C) and bean micronisation time (T = 60 s), increasing the beans size from 4 mm to 6 mm leads to a decrease in the specific energy consumption from 62.57 Wh·kg^{-1} to 46.97 Wh·kg^{-1}, respectively, which is explained by the productivity increase (kg·h^{-1}) of the experimental device. It proves that using soybeans with a larger size in micronisation is more efficient from the point of view of the specific energy consumption. Meanwhile, it should be noted that defining the soybean size influence on the urease activity and specific energy consumption during the micronisation is not found in the works of other researchers.

The evaluation of the micronisation quality was conducted by the index of the urease activity in units of ΔpH. It is much easier to determine the urease activity in the beans than the content of the trypsin inhibitors (Ruis 2013; Morgunova et al. 2020). If it is necessary to determine the content of the trypsin inhibitors, we can use the functional dependence between the level of the trypsin inhibitors and the urease activity (Ruis 2013). This can be seen also in the paper of Vagadia et al. (2017).

During the experiment, a non-composite plan of the second order was implemented (Spiridonov 1981; Ferreira et al. 2007), which made it possible to reduce the number of experiments and reduce the cost of the experiment in comparison with the corresponding rotatable central composite plan.

We suppose that the further studies in the field of fodder production are reasonable to be directed on determining the regimes of the soybean micronisation to minimise the specific energy consumption while ensuring the level of anti-nutrient inactivation within the limits of the valid standards.

CONCLUSION

The process of soybean thermal treatment while using infra-red rays determined that the inactivation of the anti-nutrients in soybeans to acceptable standards values (ΔpH < 0.2) during their heat treatment requires a specific energy consumption of more than 53 Wh·kg^{-1}. The use of a non-composite second-order plan in the experimental planning made it possible to reduce the number of experiments without compromising the quality of the results. The evaluation of the obtained mathematical models using Fisher's test showed a rather high level of accordance between the analytical and practical results of the research. The functional dependence of the level of anti-nutrient inactivation and specific energy consumption on the most influential factors, such as the temperature in the micronisation zone, heat treatment time and bean size, is new to our research, and allows the optimisation of this process and improvement of the technical means for its implementation.

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