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Experimental-Statistical Analysis and Multifactorial Process Optimization of the Crust from Melon Pulp Separation Process

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Abstract: The method of the conducting an experiment on the separation of the crust from melon at the pilot unit were suggested and the search for optimal regimes of its work by statistical modeling methods were performed. The objects of study were late ripening varieties: Kalaysan, Thorley, Gulab-sary. For the study central composite rotatable uniform planning and fractional factorial experiment were used. Rational ranges of input factors values such as the ratio of the rotation frequency of the abrasive drum to the rotation frequency of the supply drum, the value of the grinding gap between the supply drum and cutting knife, the cutting knife sharpening angle, the number of supply drum spikes at grip zone, diameter of the abrasive drum hole. The planning method with the processing planning matrix in a design expert v. 10 Software module is applied to obtain regression equations that adequately describe the actual process. Their graphical interpretation is presented by curves of equal values and engineering nomograms that allow to predict a choice of rational values of input factors based on the three optimization criteria: the specific energy consumption of the cutting process, the specific performance per pulp and pulp extraction ratio (ratio of extracted pulp to the total weight of the slices).

Key words: Melon, optimization, multi-factorial analysis, extraction ratio, gulab-sary

INTRODUCTION

The culinary fruits are a perspective resource of vegetable raw materials for the production of various food products. Products from the culinary fruits are used in the fresh or processed form. Melon is one of the economically important and widely cultivated fruits in the world (Medvedkov *et al*., 2015; Pech *et al*., 2007; Li *et al*., 2006).

Dietary and health benefits of melon are very high. The use of melons in food technology help to promote the immune system of the body, to get rid of toxins and cholesterol, to treat disorders in digestive tract, urinary tract and cardiovascular system, to normalize metabolism (Amaro *et al*., 2015; Perez *et al*., 2013).

The pulp of melon is a delicious dessert food. It is like a jam, canned fruit drinks and other canned foods, blended juices and frozen foods. Melon skin is a raw material which can be used to produce pectin or used as a highly-nourishing additive in flour production. Pectin is used as a natural detoxicant, key component of a drug production and used as a thickening and gelling agent in the food industry.

The seeds are the raw material for the production of vegetable oil, comparable in their properties with the best varieties of olive oil. Furthermore, it is well known that in the melon's seeds contain oil which is used abroad in cosmetics and can be used as biologically active dietary supplements (Derevenko, 2013; Kasyanov, 2010; Sayed and Ahmed, 2013; Oluwabamiwo *et al*., 2015; Sannikova *et al*., 2015).

Depending on the seeds processing method from oilcakes can be produced highly-nourishing flour which is used as an additive in functional food products (Kasyanov, 2010). The solid residues left after the oil is extracted contain about 60% protein. It can be processed into flour for various dietary products which includes meat analogue (Oluwabamiwo *et al*., 2015).

Currently, in the Republic of Kazakhstan only dried pulp is received from melon fruits. All processes related to the primary processing melons in particular, peeling, cutting and pulp grinding are executed mainly manually and the existing technological design solutions for peeling machines to peel fruits do not provide efficient and high quality work. Implementation of melon deep processing to obtain functional and long-term storage food products, juices including blended fruit and vegetable juices, oils and pectin requires special universal equipment for peeling melon fruits from peel and seeds, grinding pulp with a high performance and low energy consumption (Li *et al*., 2006).

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MATERIALS AND METHODS

The most complex technological operation in the melon processing is separation of melon peel from the melon pulp and simultaneously pulverizing pulp. However, the lack of scientific and experimental base of this process step hinders the development of high-performance machines for these operations.

In this regard, the method of the conducting an experiment on the separation of the crust from melon in the pilot unit were proposed and the search for optimal regimes of its work by statistical modeling methods were conducted. The objects of study were late ripening varieties: kalaysan, thorley, gulab-sary, they are used for the processing and production of the different long-storage products; these melon varieties have a high storage life. The search for conditions to study the interaction of various factors affecting to separation process of the melon skins were performed.

For the study purposes a central composite rotatable uniform planning and fractional factorial experiment were used. Rational intervals of input factors values such as the ratio of the rotation frequency of the abrasive drum to the rotation frequency of the supply drum, the value of the grinding gap between the supply drum and cutting knife, the cutting knife sharpening angle, the number of supply drum spikes at grip zone, hole diameter of the abrasive drum.

The planning method with the processing planning matrix in a design expert v.10 Software module is applied to obtain regression equations that adequately describe the actual process. Their graphical interpretation is presented by curves of equal values and engineering nomograms that allow to predict a choice of rational values of input factors based on the three optimization criteria: the specific energy consumption of the cutting process, the specific performance per pulp and pulp extraction ratio (ratio of extracted pulp to the total weight of the slices).

The obtained data can be used in the operational management of the technological parameters of the process based on their bilateral restrictions under random perturbation conditions both from the geometrical dimensions of melon and its inhomogeneous composition.

Theory: Experimental set-up to separate the skin from melon (Fig. 1) contains: abrasive drum, supply drum with spikes, cutting knife, collecting launder (hopper), launder for discharging pulp (pulp gutter), drive gears ofabrasive and supply drum, soleplate.

Preformed melon slices are fed through the collecting launder inside the working zone where by supply drum spikes are drawn into the gap between the drums. Spikes pierce the peel without damaging, performing the function of its movement.

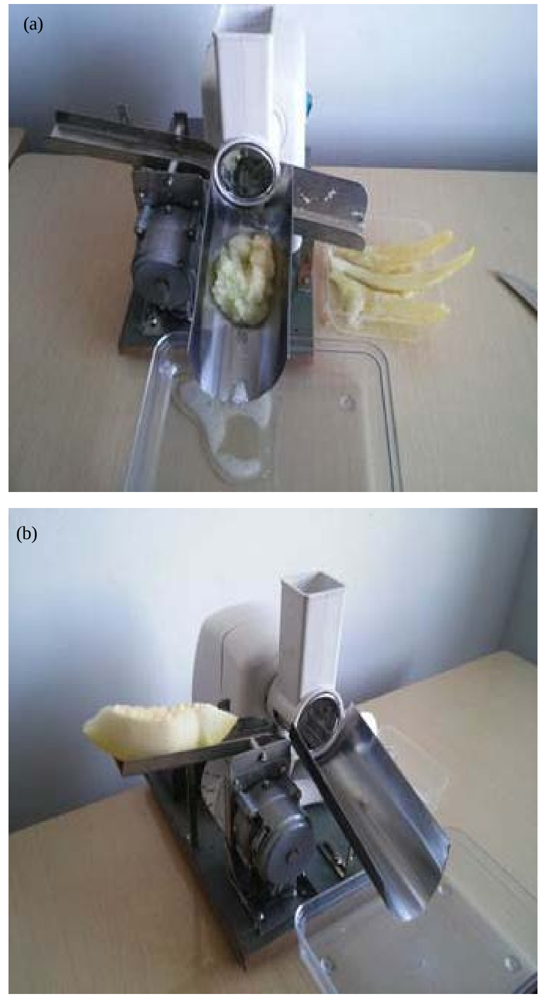

Fig. 1: Pilot unit to separate the skin from melon

Meanwhile melon pulp through the inlet of the abrasive drum enters the pulp gutter and pulp separated from the unit and cutting knife cuts off the rest of the pulp from the inner surface of the abrasive drum into the pulp gutter. Freed from the pulp, skin is outputted from unit as an after product.

The objects of study were late ripening varieties: kalaysan, thorley, gulab-sary, since these varieties are used for the processing and production of the different long-storage products according to the melon varieties classification proposed by Admaeva (Amaro *et al*., 2015).

Furthermore, these melon varieties have a high storage life in comparison with early and mid-late ripening varieties which allows to extend the deadline for the processing of raw materials as a result to improve the production efficiency of the melon processing line. Such varieties have oval-elongated shape, allowing as much as possible to mechanize melon peeling process with simultaneous cutting it into slices of a given size.

Optimization of process of crust separation from melon pulp: The search for the optimal regimes to study the interaction of various factors affecting to process of cutting the melon crust were performed. For these purposes mathematical planning method was used. The mathematical description of this process can be obtained empirically.

Here in, its mathematical model takes the form of the regression equation found by using statistical methods based on performed experiments. A mathematical model of the process under study is presented in the second-degree polynomial form:

$$Y = b_0 + \sum_{i=1}^{n} b_i X_i + \sum_{i=1}^{n} b_{ii} X_i^2 + \sum_{i \le j}^{n} b_{ij} X_i X_j \quad (1)$$

Where:

b_0 = Free term of the equation equal to the average value of the response under conditions that the considered factors lie in the middle, "zero" levels

X = Scale factors that determine the response function and yield variation

b_{ij} = Coefficients of two-factor interactions that show how much the influence degree of of one factorchanges in case of second factor value change

b_{ii} = Coefficients of quadratic effects that determine the non-linearity of the output parameter from the considered factors

i, j = Factors indixes

n = The number of factors in the planning matrix

Justification of the choice of the input factors variation limits: As the main factors influencing the process of cutting a melon crust, the following factors have been chosen:

- X_1 = Ratio of the rotation frequency of the abrasive drum to the rotation frequency of the supply drum (c^{-1}/c^{-1})
- X_2 = Value of the grinding gap between the supply drum and cutting knife (mm)
- X_3 = Cutting knife sharpening angle (deg)
- X_4 = Number of supply drum spikes at grip zone (PCS)
- X_5 = Diameter of the abrasive drum hole (mm)

Table 1: Range of input factors variation

Planning conditions	Coded value	Range of input factors variation: X_1 (c^{-1}/c^{-1} s^{-1}/s^{-1})	X_2 (mm)	X_3 (deg)	X_4 (T. psc)	X_5 (mm)
Center point	0	10.0	5	40	6	4
Low level	+1	12.5	7	55	7	5
High level	-1	7.5	3	25	5	3
Top axial point	+2	15.0	9	70	8	6
Bottom axial point	-2	5.0	1	10	4	2

Table 2: Formulation of the optimization goal

Constraints names	Goal	Lower limit	Upper limit	Lower weight	Upper weight	Importance
X_1 (s^{-1}/s^{-1})	Is in range	5.00	15.00	1	1	3
X_2 (mm)	Is in range	1.00	9.00	1	1	3
X_3 (deg)	Is in range	10.00	70.00	1	1	3
X_4 (pst)	Is in range	4.00	8.00	1	1	3
X_5 (mm)	Is in range	2.00	6.00	1	1	3
Y_1 (W/kg)	minimize	1.19	1.71	1	5	4
Y_2 (g/sec)	Is target = 85	56.00	90.00	5	4	3
Y_3 (%)	Is target = 92	81.00	95.00	2	3	5

Table 3: Optimization task solution

Solution number	X_1 ($s^{-1}s^{-1}$)	X_2 (mm)	X_3 (deg)	X_4 (pst)	X_5 (mm)	Y_1 (W/kg)	Y_2 (g/sec)	Y_3 (%)	Desirability
1	10.09	3.01	12.27	7.08	5.82	1.13	85	92	1
2	11.43	4.42	12.66	7.88	5.73	1.15	85	92	1
3	10.18	1.98	16.18	6.58	5.78	1.18	85	92	1
4	11.95	4.97	12.91	7.90	5.55	1.19	85	92	1
5	10.03	3.40	10.24	7.15	5.77	1.12	85	92	1
6	10.66	4.12	10.56	7.74	5.80	1.11	85	92	1
7	11.82	4.57	13.95	7.82	5.65	1.19	85	92	0.990
8	12.15	3.57	18.22	8.00	5.90	1.18	85	91	0.982
9	11.45	5.05	10.05	7.45	5.39	1.19	84	91	0.978
10	11.65	5.05	11.29	7.68	5.46	1.19	84	90	0.974
etc.	etc.	etc.	etc.	etc.	etc.	etc.	etc.	etc.	etc.

All given factors are compatible and uncorrelated with each other. The range choice of input factors variation is defined by processing conditions. Variation limits of factors under study are given in Table 1. The search for optimal regime parameters of process.

Finding the optimum solutions and optimization tasks were carried out by using the desirability function d [...] where each Y_i transferred to $d_i \in \{0...1\}$. If Y_i determines the objective function of optimum (maximum or minimum value) or optimum value is specified, conditioned by economic expediency, then d_i = 1. In the case when the optimum value does not match the interval of predetermined values $Y_j \notin \{0...1\}$ the d_i = 0. After determining d_i for each Y_j the maximum value of desirable function according to the equation was determined:

$$D = (d_1 d_2 \ldots d_j)^{(1/j)} \quad (2)$$

In accordance to the comparative evaluation of the obtained set values of desirable function D the optimum (unique) solution of multi-criteria optimizationin the area of the input factors variation, in terms of output information factors on Y_j were selected. Optimization task is formulated in such way (Table 2). First 10 solutions are collected in Table 3.

RESULTS AND DISCUSSION

The range choice of input factors variation is defined by processing conditions such as skin separation from melon as well as technical and economic indicators. The criteria for assessing the impact of various factors on the process of cutting were chosen:

- Y_1 = the specific energy consumption of the cutting process (Vt/kg)
- Y_2 = the specific performance per pulp (g/sec)
- Y_3 = the specific performance per pulp and pulp extraction ratio (ratio of extracted pulp to the total weight of the slices) (%)

For the study a central composite rotatable uniform planning and fractional factorial experiment FFE 25-1 is used. The number of experiments in the planning matrix with given five input parameters is 32. The research program was incorporated into the experiment planning matrix (Table 4).

Regression equations and their analysis: Table 5-6 shows the ANOVA analysis results for the quadratic model equation of the output factor Y_1. F-value of 3.11 for the free term of the equation is physically meaningful. At the same time 2.87% the probability that this value contributes to noise. Values “Prob.>F” of <0.05 indicates that all model terms are meaningful. In this case, A-E are meaningful.

F-value “Lack of Fit” equal to 11.46 means that the losses in the processing of the experiment results are at acceptable level. However, only 0.85% probability that the F-value “Lack of Fit” are derived from the noise of the model. “Adeq precision” measures ratio of signal to noise. The obtained value of 7.62 shows adequate signal. The given model can be used for further calculations. After processing the planning matrix in design expert v.10 (Perez *et al*., 2013). Software module, the following regression equations were obtained:

$$Y_1 = 1.45 + 0.046X_1 - 0.041X_2 + 0.043X_3 + 0.035X_4 - 0.09X_5 - 5.00E\text{-}03 \cdot X_1^2 - 0.113X_2^2 - 0.150X_3^2 - 0.125X_4^2 - 0.127X_5^2 \quad (3)$$

$$Y_2 = 69.67 + 5.54X_1 - 2.21X_2 - 2.29X_3 + 2.04X_4 + 1.96X_5 - 0.69X_2X_3 + 0.56X_2X_4 - 1.06X_3X_5 - 0.81X_4X_5 + 0.08X_1^2 + 0.20X_2^2 + 0.20X_3^2 - 0.80X_4^2 + 0.58X_5^2 \quad (4)$$

Table 4: Experiment planning matrix

Experiment numbers	X_1 (s^{-1}/s^{-1})	X_2 (mm)	X_3 (deg)	X_4 (pst)	X_5 (mm)	Y_1 (W/kg)	Y_2 (g/sec)	Y_3 (%)
1	7.5	3	25	5	5	1.300	69	88
2	12.5	3	25	5	3	1.480	71	95
3	7.5	7	25	5	3	1.340	60	82
4	12.5	7	25	5	5	1.320	77	85
5	7.5	3	55	5	3	1.470	62	89
6	12.5	3	55	5	5	1.400	76	85
7	7.5	7	55	5	5	1.280	61	89
8	12.5	7	55	5	3	1.410	70	87
9	7.5	3	25	7	3	1.490	67	95
10	12.5	3	25	7	5	1.390	80	94
11	7.5	7	25	7	5	1.240	72	86
12	12.5	7	25	7	3	1.530	78	90
13	7.5	3	55	7	5	1.350	67	89
14	12.5	3	55	7	3	1.590	77	92
15	7.5	7	55	7	3	1.480	65	87
16	12.5	7	55	7	5	1.400	75	83
17	5.0	5	40	6	4	1.300	56	83
18	15.0	5	40	6	4	1.570	82	95
19	10.0	1	40	6	4	1.540	80	95
20	10.0	9	40	6	4	1.280	59	82
21	10.0	5	10	6	4	1.210	78	93
22	10.0	5	70	6	4	1.580	61	84
23	10.0	5	40	4	4	1.310	62	86
24	10.0	5	40	8	4	1.500	69	92
25	10.0	5	40	6	2	1.710	66	91
26	10.0	5	40	6	6	1.190	76	81
27	10.0	5	40	6	4	1.450	70	90
28	10.0	5	40	6	4	1.420	68	92
29	10.0	5	40	6	4	1.470	71	89
30	10.0	5	40	6	4	1.490	70	89
31	10.0	5	40	6	4	1.410	69	90
32	10.0	5	40	6	4	1.460	72	90

Table 5: ANOVA for response surface quadratic model response 1 (Y_1, W/kg)

Indexes	Sum of squares	df	Mean square	F-values	p-values Prob.>F
Model	3.83E-01	20	1.92E-02	3.11E+00	2.87E-02
X_1 (s^{-1}/s^{-1})	5.13E-02	1	5.13E-02	8.32E+00	1.48E-02
X_2 (mm)	4.08E-02	1	4.08E-02	6.62E+00	2.59E-02
X_3 (deg)	4.42E-02	1	4.42E-02	7.17E+00	2.15E-02
X_4 (pst)	3.01E-02	1	3.01E-02	4.88E+00	4.93E-02
X_5 (mm)	1.93E-01	1	1.93E-01	3.12E+01	1.63E-04
X_1X_2	3.06E-04	1	3.06E-04	4.96E-02	8.28E-01
X_1X_3	1.06E-03	1	1.06E-03	1.71E-01	6.87E-01
X_1X_4	1.06E-03	1	1.06E-03	1.71E-01	6.87E-01
X_1X_5	7.56E-04	1	7.56E-04	1.23E-01	7.33E-01
X_2X_3	6.25E-06	1	6.25E-06	1.01E-03	9.75E-01
X_2X_4	1.06E-03	1	1.06E-03	1.71E-01	6.87E-01
X_2X_5	3.06E-04	1	3.06E-04	4.96E-02	8.28E-01
X_3X_4	1.56E-04	1	1.56E-04	2.53E-02	8.76E-01
X_3X_5	3.06E-04	1	3.06E-04	4.96E-02	8.28E-01
X_4X_5	6.01E-03	1	6.01E-03	9.74E-01	3.45E-01
X_1^2	7.33E-04	1	7.33E-04	1.19E-01	7.37E-01
X_2^2	3.71E-03	1	3.71E-03	6.02E-01	4.54E-01
X_3^2	6.60E-03	1	6.60E-03	1.07E+00	3.23E-01
X_4^2	4.58E-03	1	4.58E-03	7.43E-01	4.07E-01
X_5^2	4.58E-05	1	4.58E-05	7.43E-03	9.33E-01
Residual	6.79E-02	11	6.17E-03	-	-
Lack of fit	6.33E-02	6	1.05E-02	11.46	8.54E-03
Pure error	4.60E-03	5	9.20E-04	-	-
Cor total	4.51E-01	31	-	-	-

Table 6: Assessment of the adequacy of model

Statistics	Values
SD	7.85E-02
Mean	1.42E+00
CV (%)	5.54E+00
Press	1.70E+00
-2 Log likelihood	-1.06E+02
AICc	2.82E+01
R^2	8.50E-01
Adj R^2	5.76E-01
Pred R^2	-2.77E+00
Adeq precision	7.62E+00
BIC	-3.34E+01

$$Y_3 = 89.86 + 1.25X_1 - 2.67X_2 - 1.33X_3 + 1.17X_4 - 1.58X_5 - 0.25X_1X_2 - 1.25X_1X_3 - 1.00X_1X_5 + 1.25X_2X_3 - 0.62X_2X_4 + 0.75X_2X_5 - 0.87X_3X_4 - 0.24X_2^2 - 0.25X_3^2 - 0.86X_5^2 \quad (5)$$

Graphical interpretation of Eq. 2-4 in the form of equal values curves and the response surface is shown in Fig. 2-4. The influence of input factors X_i, i = (1. 5) on output factors Fig. 5-7, $Y_{i,j} = \overline{(1.3)}$ was defined.

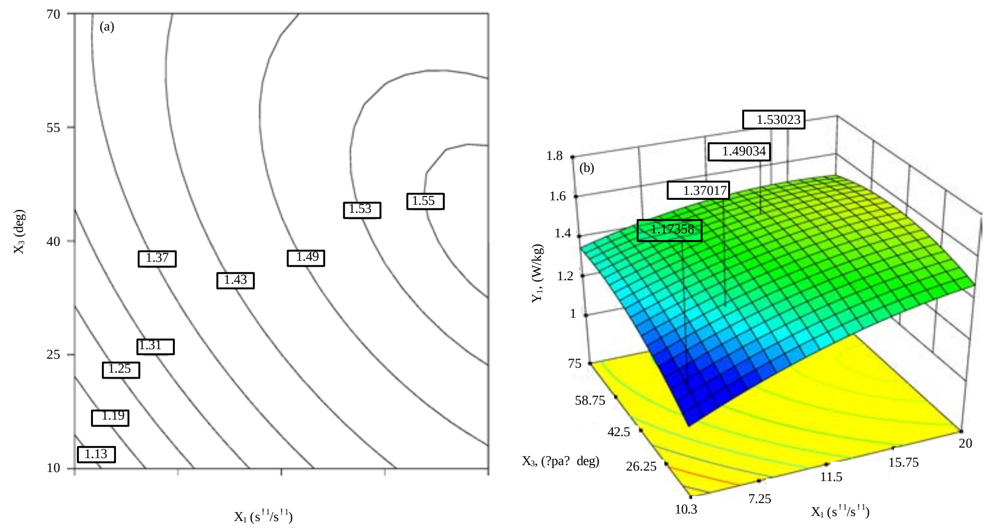

Fig. 2: Contour plot: a) and surface response and b) depending on the specific energy consumption in the process of cutting Y_1 (W/kg) by: the ratio of the rotation frequency of the abrasive drum to the rotation frequency of the supply drum X_1 (s^{-1}/s^{-1})and the cutting knife sharpening angle X_3 (deg)

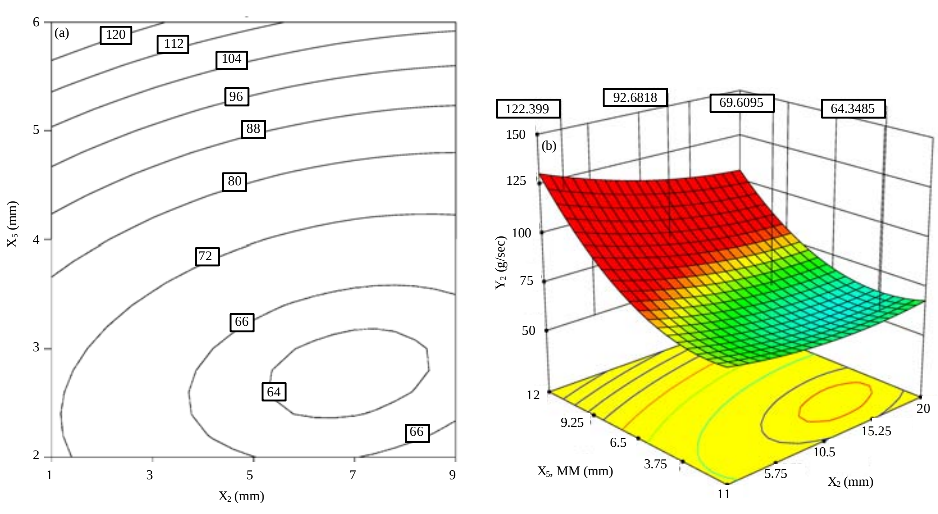

Fig. 3: Contour plot: a) and the response surface and b) depending on the specific performance per pulp Y_2 (kg/sec) of: grinding gap between the supply drum and the cutting knife X_2 (mm) and diameter of the abrasive drum hole (X_5) (mm)

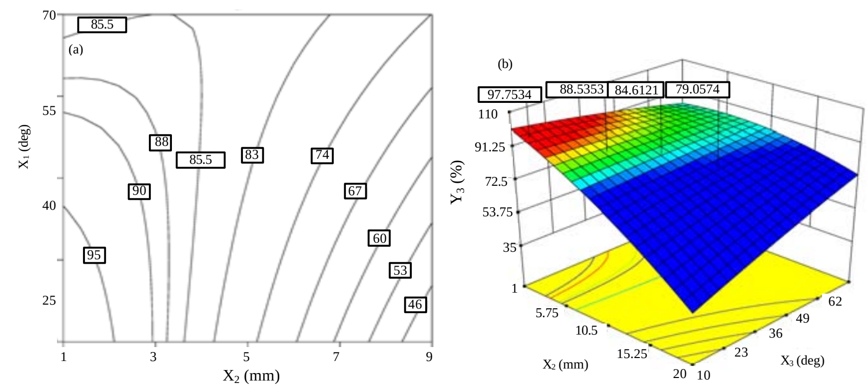

Fig. 4: Contour plot: a) and the response surface and b) depending on the pulp extraction ratio Y_3 (%) of: grinding gap between the supply drum and the cutting knife X_2 (mm) and cutting knife sharpening angle X_3 (deg)

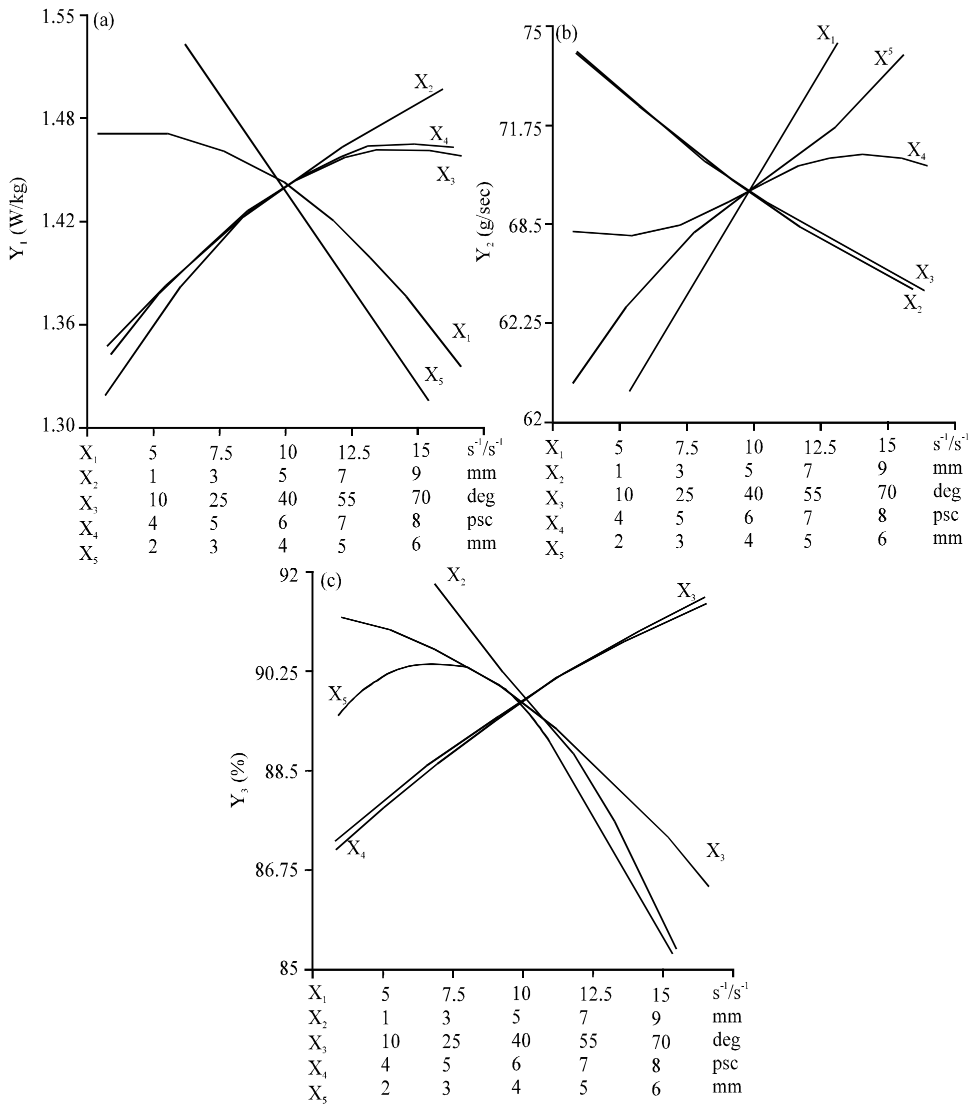

Fig. 5: Impact of the input factors X_1 on specific energy consumption in the process of cutting, Y_1 (W/kg) b), specific performance per pulp Y_2 (kg/sec) b) and pulp recovery ratio Y_3 (%)

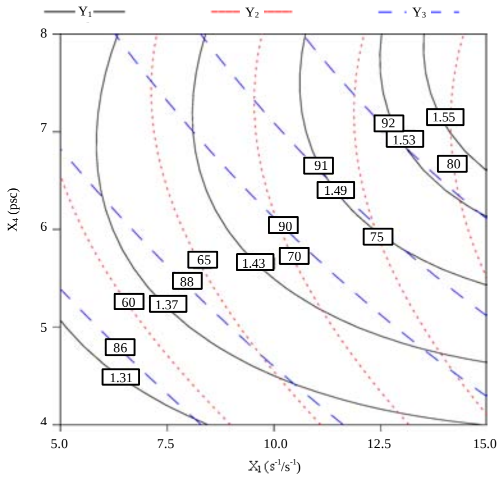

Fig. 6: The nomogram for the determination of the ratio of the rotation frequency of the abrasive drum to the rotation frequency of the supply drum (X_1), s^{-1}/s^{-1} and the number of supply drum spikes at grip zone, psc by output factors Y_j

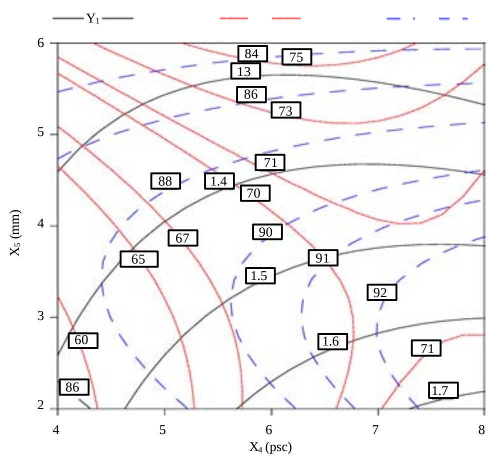

Fig. 7: The nomogram for determination of the number of supply drum spikes at grip zone X_4 psc and diameter of the abrasive drum hole X_5 mm by output factors Y_j

The graphical interpretation one of optimization solutions for the different pairs of input parameters at D→1 is given in Fig. 8. Output factor tends to the maximum value:

$$d = \begin{cases} 0 & y < L \\ \left(\frac{y-L}{T-L}\right)^r & L \le y \le T \\ 1 & y > T \end{cases} \quad (6)$$

Where:

T = Target value

L_U = Lower and upper limits of the output factor interval

r = Index "influence (impact)" of the desirability function (weighting factor)

When r = 1-d is a linear function; r>1 gives a greater impact on the shift d to the target valuel, 0<r<1 less important degree of influence. Output factor tends to the minimum value:

$$d = \begin{cases} 1 & y < T \\ \left(\frac{U-y}{U-T}\right)^r & T \le y \le U \\ 0 & y > U \end{cases} \quad (7)$$

Output factor tends to the given numeric value:

$$d = \begin{cases} 1 & y < L \\ \left(\frac{y-L}{U-T}\right)^{r_1} & L \ge y \ge T \\ \left(\frac{U-y}{U-T}\right)^{r_2} & T \le y \le U \\ 0 & y > U \end{cases} \quad (8)$$

Multiparameter optimization problem was formulated as follows: to find such values of regime parameters of the melon pulp from the crust separation process which would have required a minimum of energy consumption, reach maximum performance of pulp and a maximum pulp recovery rate from the melon slices under limited input parameters (Table 1).

Since, the selected optimization criteria are equally important and characterized by their equivalence, the indicators of their "influence" on the desirability function are taken to equal one, r = 1.

The value from the D array of solutions D→was selected Fig. 9, in accordance with which the rational intervals of input factors values were set: X_1 = 8...10 c^{-1}/c^{-1}; X_2 = 1...3 mm; X_3 = 11...13 deg; X_4 = 6..7 pcs.; X_5 = 5...6 mm. A series of parallel experiments were run to verify the correctness of the results. The results were within the calculated confidence intervals for all selected performance quality criteria. The mean square error does not exceed 12.4%.

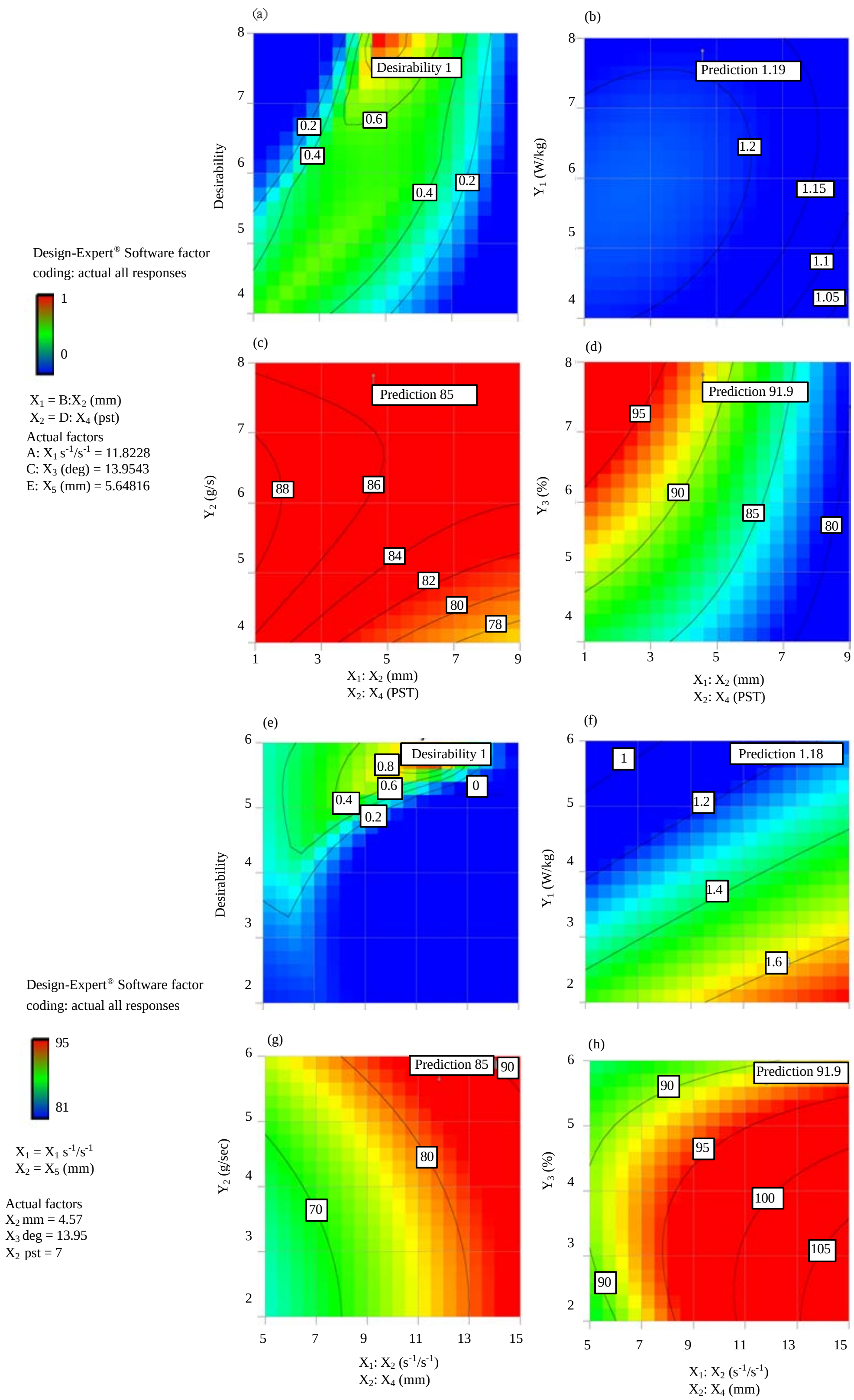

Fig. 8: Desirability function d for solving the optimization problem was divided into three special cases

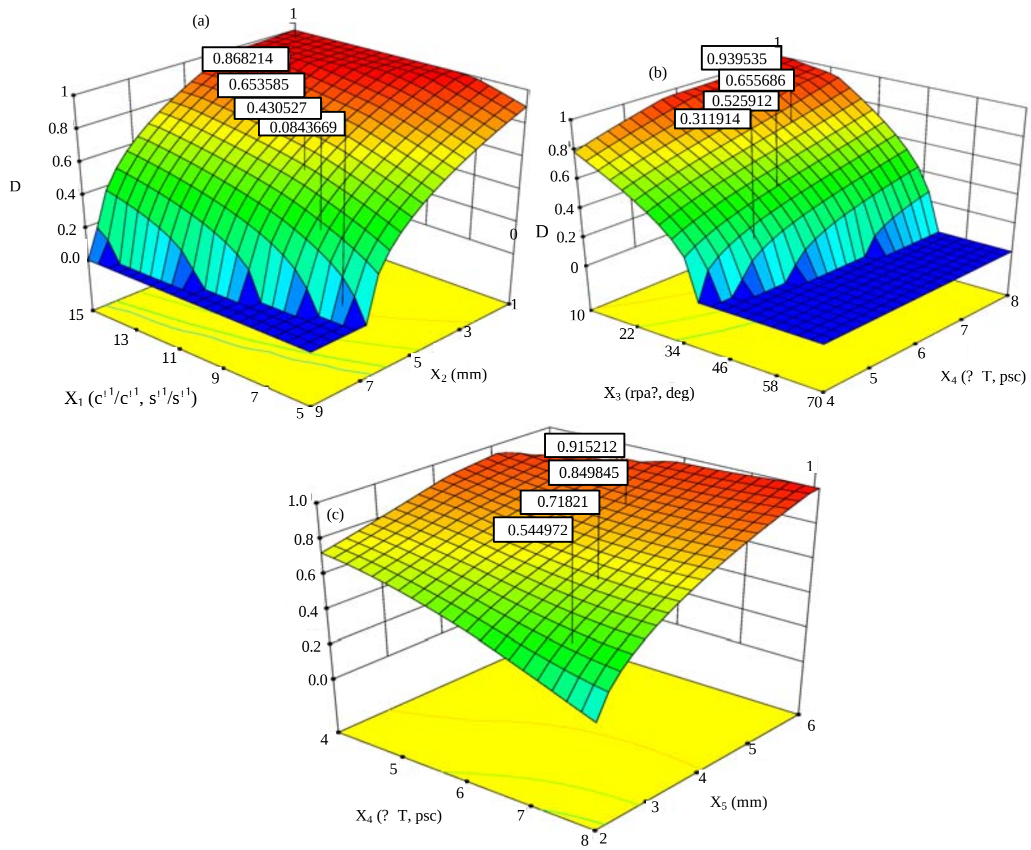

Fig. 9: Determination of the desirability function for the specified criteria optimization

CONCLUSION

The use of planning method with the processing matrix of planning in a Design Expert V.10 Software module is allowed to obtain regression equations that adequately describe the actual process and their graphical interpretation is presented by curves of equal values and engineering nomograms that allows to predict a choice of rational values of input factors based on the three optimization criteria. The obtained data can be used in the operational management of the technological parameters of the process based on their bilateral restrictions under random perturbation conditions both from the geometrical dimensions of melon and its in homogeneous composition.

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