The paper is devoted to the study of the interaction and significance of factors influencing the prediction and optimization of the process of obtaining malt. The object of our research is wheat, barley and rye malt. 33 full factorial experiments were performed, germination period, wetting degree and temperature act as variable factors. At the same time, the amylolytic activity of malt's enzymatic complex and malt's saccharification ability were taken as the response function of the experiment. 27 experiments were carried out with three repetitions in order to check the accuracy of the choice of optimal conditions for the process of obtaining malt, and a regression equation was obtained. According to the least squares method, the regression equations were obtained for approximation of the saccharification ability (SA) and amylolytic activity (AA) values of wheat malt. According to the method of regression analysis, the adequacy of the equations was checked by the Fisher criterion, the statistical significance of their coefficients was checked by the Student's criterion, and the homogeneity of parallel experiments was checked by the Cochrane criterion. The regression model expressing the result of the optimization of the process of obtaining wheat malt is as follows: τ=5.8 days, w=42.2 %, t=15.9 °C; Y_{SA}=5.35, Y_{AA}=320.0, for barley malt – τ=6.1 days; w=44.1 %; t=17.6 °C; Y_{SA}=4.93; Y_{AA}=255.2, and for rye malt – τ=4.6 days; w=45.1 %; t=15.0 °C; Y_{SA}=8.63; Y_{AA}=198.1. In this work, the temperature dependence of the amylolytic activity and saccharifying activity of malt enzymes was also studied. The germination temperature of grains has a maximum effect on the complex of amylolytic enzymes of malts.

The research materials can be applied in the production of non-alcoholic and functional beverages

Keywords: grains, malting, modeling, optimization, amylolytic activity, saccharifying activity, functional beverages

UDC 664.644.51

DOI: 10.15587/1729-4061.2023.289421

DEVELOPMENT OF A MODEL AND OPTIMIZATION OF THE INTERACTION OF FACTORS IN THE GRAIN MALTING PROCESS AND ITS APPLICATION IN THE PRODUCTION OF FUNCTIONAL BEVERAGES

Natavan Gadimova
Corresponding author
Candidate of Technical Sciences, Associate Professor
Department of Engineering and Applied Sciences
Department of Food Engineering
Azerbaijan State University of Economics (UNEC)
Istiqlaliyyat ave., 6, Baku, Azerbaijan, AZ 1001
E-mail: natavan.qadimova@mail.ru

Hasil Fataliyev
Doctor of Technical Sciences, Professor*

Elnur Heydarov
Candidate of Technical Sciences, Associate Professor*

Yusif Lezgiyev
PhD Student*

Simuzar Isgandarova
Assistant
Department of Chemistry**
*Department of Food Engineering and Expertise**
**Azerbaijan State Agricultural University
Ataturk ave., 450, Ganja, Azerbaijan, AZ 2000

Received date 17.08.2023
Accepted date 21.10.2023
Published date 30.10.2023

***How to Cite**: Gadimova, N., Fataliyev, H., Heydarov, E., Lezgiyev, Y., Iskenderova, S. (2023). Development of a model and optimization of the interaction of factors in the grain malting process and its application in the production of functional beverages. Eastern-European Journal of Enterprise Technologies, 5 (11 (125)), 43–56. doi: https://doi.org/10.15587/1729-4061.2023.289421*

1. Introduction

Cereals are important staple crops and major providers of nutrients and energy, and are rich in bioactive phytochemicals with health benefits. Cereal grains include a wide range of biologically active phytochemicals such as phenolic compounds, carotenoids, dietary fiber, phytosterols, tocols, gamma oryzanol, and phytic acid [1].

Wheat and barley are traditionally used in the production of beverages. There are studies evaluating the potential of rye malt for beverage production. Sensory evaluation has shown that malting produces pleasant malt and caramel aromas. Barley lost its characteristic malt volatiles during storage and formed aging compounds, nut pyrazines and caramel furanones remained dominant in rye malt even after storage [2].

The beverage production technology includes several stages, the main one being the production of malt. The quality of the resulting malt plays an important role in obtaining a quality drink in the end. Therefore, optimization and modeling of the malting process play an important role. Since modeling of the malting process takes into account all the main factors influencing the process and gives a high reliability of obtaining the best results. Factors affecting the quality of malt include germination time, wetting degree, and process temperature.

Optimizing the malting process also makes it possible to obtain the best results. Process modeling establishes the relationship between the individual stages of the technological cycle and as a whole sieves the optimization process. Therefore, research on optimizing the parameters of malt for the production of functional beverages is relevant.

2. Literature review and problem statement

The malting process is influenced by factors such as germination time, wetting degree and process temperature. The choice of optimal values of these indicators significantly affects the quality of the resulting malt. Depending on the tasks set, as well as ways to study the influence of various parameters on the malting process, different results can be obtained. A solution to this problem may be to conduct a multivariate analysis of these indicators. In contrast to decoding a single-criteria problem, multi-sriteria optimization by calculating multiple optimal solutions is widely accepted [3].

Response surface methodology (RSM) was applied to optimize the malting process of a local variety of bread wheat [4] and clarified spelt [5].

Coca – sr [6] applied Response Surface Methodology (RSM) using Central Composite Design (CCD).

Scientists investigated the drying kinetics of barley grains using mathematical modeling to evaluate the diffusion coefficient during and after drying to evaluate the effect of high drying temperatures on the seed germination index for malt production [7]. These studies are limited to the specific objectives set.

Depending on the tasks set, as well as by studying the influence of various parameters on the malting process, different results can be obtained.

As we can see, there are studies related to the optimization of the process of producing malt from wheat. The influence of germination time, wetting degree and temperature on the process of producing malt from barley and rye has not been sufficiently studied.

It should be noted that mixing various grains, such as cereals, pseudo-grains, legumes and millet [8], according to the right recipes can lead to obtaining beverages with a given set of indicators [9]. There are studies where, using QbD, a premix for grain carbonated drinks with an adequate nutritional composition has been developed [10], as well as beer containing malt and non-malt substitutes [11]. Mixing various grains gives beverages a unique taste and aroma, enriches them with a set of vitamins and microelements contained in sprouted grains. Therefore, in our studies we used cereals such as wheat, barley and rye.

3. The aim and objectives of the study

The aim of the study is to optimize the germination modes of several cereals according to the criteria: germination time, wetting degree and germination temperature. This will reduce costs during the malting process and improve the quality of the resulting malt.

To achieve this aim, the following objectives are accomplished:

– to optimize the wheat malting process depending on germination time, wetting degree and germination temperature;

– to optimize the barley malting process depending on germination time, wetting degree and germination temperature;

– to optimize the rye malting process depending on germination time, wetting degree and germination temperature;

– to investigate the temperature dependence of the amylolytic activity and saccharifying ability of the enzymatic complex of wheat, barley and rye malts.

4. Materials and methods

In experiments on malt production, wheat, barley and rye were used. The experiments were carried out in laboratory conditions. The main physico-chemical indicators of grains are given in Table 1.

Table 1

Main physico-chemical indicators of grains

Indicator	Wheat	Barley	Rye
Garbage, %	1.0	1.0	1.0
Humidity, %	9.8	9.4	9.6
Natur.mass, q/dm^3	630	600	610
Starch, %	57.4	53.1	58.2
Protein, %	11.5	11.8	12.7
Germination on the 3rd day, %	82.2	83.7	83.7

Samples of wheat, barley and rye were washed with water at a temperature of 14 °C. After the cereals were soaked in water at a temperature of 14 °C, germination was carried out at temperatures of 14 °C, 16 °C and 18 °C. To prevent grain caking, as well as to provide oxygen access, they were mixed. 3^3 factorial experiments were conducted in all types of grain. The germination capacity on the third day was the same in barley and rye (83.7 %), slightly less in wheat (82.2 %).

Statistical analysis was employed to analyze the obtained values. The adequacy of the regression equation was determined by the Fisher criterion when experimental values were used. According to the research program, the goal of the experiment is to achieve the maximum of quality (y) and the minimum of costs (y_2). In the technical process, dependencies on the input factors that provide such a purpose function have been determined. These dependencies are included in the line of the response function (target function) and its summaries in a linear form as a product of factors of the first degree:

$$y_1=b_0+b_1x_1+b_2x_2+b_3x_3+b_{12}x_1x_2+ +b_{13}x_1x_3+b_{23}x_2x_3+x_1x_2x_3, \quad (1)$$

$$y_2=b'_0+b'_1x_1+b'_2x_2+b'_3x_3+b'_{12}x_1x_2+ +b'_{13}x_1x_3+b'_{23}x_2x_3+b'_{123}x_1x_2x_3. \quad (2)$$

Here b_0, b_{123}, b'_0, b'_{123} are the corresponding regression coefficients with coded values in the equation.

To convert factors from their real values to coded form, the following formula is used:

$$x_i^k=\frac{x_i^n-x_{io}^n}{\delta_i}. \quad (3)$$

Here, x_i^k and x_i^n are the codified and natural values of the cofficient i, respectively; x_{io}^n – i is the natural value of the factor at the level of zero (0); δ_i i is the natural value of the variation interval of the factor:

$$b_0 = \frac{\sum_{j=1}^{N} \overline{y}_1}{N}; \qquad (4)$$

– for linear factors:

$$b_i = \frac{\sum_{j=1}^{N} x_{ij}\overline{y}_i}{N}; \qquad (5)$$

– for interaction factors:

$$b_i = \frac{\sum_{j=1}^{N} x_{ij}x_{qj}\overline{y}_i}{N}. \qquad (6)$$

Here $\overline{y}_i$ – "m" is the average numerical value of the output parameters for the j-type experiment in repetition; N – the number of experiments; X_{ij} – j is the value of the i-factor in the experiment; X_{qj} – j is the value of the q-factor in the experiment.

Taking into account that some regression coefficients can be taken too small, their significance level is checked.

The regression coefficient is considered significant if its value is greater than the absolute value of the confidence interval. When using a factorial experiment, the confidence intervals are equal for all coefficients. The significance of a coefficient is determined using the Student's criterion (t):

$$t = \frac{|b_i|}{\delta_{bi}}. \qquad (7)$$

Here $|b_i|$ – the absolute value of the i-coefficient of regression; t – the Student's criterion value at the selected level of significance; δ_{bi} – the squared error of the regression coefficient. is compared to its tabular value $t_{tab}(0.05; f_y)$. Here 0.05 – the level of significance of the study; f_y – the number of degrees of freedom of the experiment:

$$f_y = N(m-1). \qquad (8)$$

Here m_j – the number of repetitions in the experiment.

The selected variance of the regression coefficient to determine the squared error (determined by the following formula)

$$\delta_{bi}^2 = \frac{\delta_y^2}{N}. \qquad (9)$$

Here δ_y^2 is the recovery dispersion:

$$\delta_{bi}^2 = \sum_{j=1}^{N} \frac{\delta_j^2}{N}. \qquad (10)$$

Here $\delta_j^2 - j -$ the variance during "m" repetitions in the experiment:

$$\delta_j^2 = \frac{\sum_{k=1}^{m} (y_1 - \overline{y}_i)^2}{m-1}. \qquad (11)$$

Here $y_j - j$ is the value of the output parameter in the experiment.

The reproducibility of the model is characterized by the homogeneity of the variances of the experiments. Homogeneity of variance is assessed using the Cochrane criterion ($G_{\max}$).

$$G_{\max} = \frac{\delta_j^2 \max}{\sum_{j-1}^{N} \delta_j^2}. \qquad (12)$$

If the calculated value of the criterion $G_{\max}$ is smaller than the table value $G_{jd}(0.05; f_N; f_u)$, then the hypothesis of homogeneity is accepted. Here, f_N is the number of free values of impulses; f_u is the number of degrees of freedom of each estimate.

$$f_u = N(m-1). \qquad (13)$$

Regression equations are tested for adequacy (the ability to accurately express the response surface).

The Fisher criterion (F) is used to evaluate the adequacy of the model. This criterion δ_a^2 is determined by the ratio of the dispersion of adequacy to the dispersion of recovery (error of experiment) δ_y^2:

$$F = \frac{\delta_a^2}{\delta_y^2}. \qquad (14)$$

Adequacy dispersion is calculated by the following formula:

$$\delta_a^2 = \frac{\sum_{a=1}^{N} (\overline{y}_j - \overline{y}_{jT})}{N-a}. \qquad (15)$$

Here $y_j - j -$ the average value of the optimization parameter during iteration "m" in the experiment; $y_{jT} - j -$ the average value of the optimization parameter calculated by means of the regression equation for the experimental conditions; a – the number of determined coefficients of the model.

İs compared with the tabular value $F_{tab}(0.05; f_a; f_y)$ where f_a is the number of degrees of freedom of the recovery variance:

$$f_a = Na. \qquad (16)$$

If $F<F_{tab}$ is true, the hypothesis of adequacy is accepted with 95 % probability, indicating that the obtained regression equation accurately represents the experimental results.

Multivariate data analysis is a suitable statistical method applied to malt production. It provides more advanced and up-to-date information than one- dimensional methods.

5. Results and analysis of modeling and optimization of the malting process of different cereals

5. 1. Modeling and optimization of the germination process of wheat malt

A 3^3 full factorial experiment was conducted to study the prediction and optimization of the wheat malt germination process and the interaction and significance of the influencing factors. The variable factors chosen were germination time (τ), wetting degree (*W*), and process temperature (*t*).

The following were taken as the response function of the experiment:

– amylolytic activity (AA) of the enzymatic complex of malt, measuered in W-K units;

– saccharifying ability (SA) of malt, measured in units/g.

The variation ranges of the units of the plan are given in Table 2.

Table 2

Variation limits of active experimental factors for obtaining wheat malt

Planning images	τ, per day	*w*, %	*t*, °C
Basic level, (0)	6	42	16
Variation interval, Δ	1	2	2
Level up (+1)	7	44	48
Low level (–1)	5	40	14

The planning matrix of the experiment is given in Table 3.

Table 3

Planning matrix and experiment results

Experiment No.	Code symbol of factors			Size of factors			Y_{AA}, W-K units	Y_{SA}, units/g
	Z_0	Z_1	Z_2	τ, per day	*w*, %	*t*, °C		
1	–1	–1	–1	5	40	14	246.7	4.16
2	0	–1	–1	6	40	14	225.8	4.26
3	1	–1	–1	7	40	14	226.4	3.77
4	–1	0	–1	5	42	14	253.6	4.23
5	0	0	–1	6	42	14	287.8	4.78
6	1	0	–1	7	42	14	242.5	4.04
7	–1	1	–1	5	44	14	251.4	4.13
8	0	1	–1	6	44	14	275.8	4.60
9	1	1	–1	7	44	14	221.5	3.69
10	–1	–1	0	5	40	16	266.3	4.44
11	0	–1	0	6	40	16	268.5	4.48
12	1	–1	0	7	40	16	262.6	4.38
13	0	0	0	5	42	16	326.4	5.44
14	1	0	0	6	42	16	345.7	5.76
15	–1	0	0	7	42	16	276.7	4.61
16	–1	0	0	5	44	16	277.4	4.62
17	0	0	0	6	44	16	282.7	4.71
18	1	0	0	7	44	16	268.5	4.48
19	–1	1	1	5	40	18	231.5	3.86
20	0	1	1	6	40	18	250.4	4.17
21	1	1	1	7	40	18	228.7	3.81
22	–1	1	1	5	42	18	242.7	4.55
23	0	1	1	6	42	18	275.6	4.59
24	1	1	1	7	42	18	235.8	3.93
25	–1	1	1	5	44	18	244.6	4.1
26	0	1	1	6	44	18	253.8	4.23
27	1	1	1	7	44	18	230.5	3.84

According to the experimental values in Table 2, regression coefficients were obtained for the approximation of SA and AA values of wheat malt using the leaset squares method. The adequacy of the coefficients was tested using the Fisher criterion in regression analysis, their significance level was tested using the Student's criterion, and the homogeneity of parallel experiments was tested using the Cochran criterion.

The evaluation of the coefficients of the regression equations is presented in Tables 4, 6 before the removal of statistically insignificant coefficients and in Tables 5, 7 after removal.

The reported value (F_{rep}=10.94) of the Fisher criterion was 4.4 times higher than the table value (F_{tab}=2.49). This shows the adequacy of the regression equation to the experiment and gives ground for accepting the hypothesis. The critical value of the Student's criterion (t_{crit}=1.74) allows determining a number of statistically insignificant coefficients. The evaluation of the significant coefficients of the regression equation after removing the insignificant coefficients is presented in Table 8.

The calculated value of the Fisher's criterion (F_{rep}=27.66) is 9.8 times greater than the table value (F_{tab}=2.82). This provides a basis for accepting the hypothesis of the adequacy of the regression coefficients to the experiment. The critical value of the Student's criterion is t_{cris}=1.72. Thus, it can be concluded that the dimensional regression equation of SA adequately expresses the dependence of wheat malt on the germination process. After removing statistically insignificant coefficients, the regression equation is as follows:

$$Y_{SA}=-2.452\cdot10^3+4.5\cdot10\tau-$$
$$-0.39\tau^2+4.880t-19.450w-0.113w^2. \quad (17)$$

According to the regression model (Table 5), the largest value of SA corresponds to (5.35) τ=5.8 days, *w*=42.2 %, *t*=15.9 °C values. The difference from the maximum experimental value (SA=5.76, τ=6 days, *w*=42 %, *t*=16 °C) is 7.1 %. With a residual variance of $S^2_{var}=0.036$ unit/g, according to equation (17), ΔY_{SA}=0.37 (unit/g)^2.

The calculated value of the Fisher's criterion (F_{calc}=10.44) was 4.2 times larger than the table value (F_{tab}=2.49), which supports accepting the hypothesis of the adequacy of the regression equation to the experiment. The critical value of the Student's criterion (t_{cris}=1.74) was used to identify statistically insignificant coefficients. The estimation of the statistically significant coefficients of the regression equation after removing the insignificant coefficients is presented in Table 7.

The calculated value of the Fisher's criterion (F_{calc}=10.44) was 4.2 times larger than the table value (F_{tab}=2.49), which supports accepting the hypothesis of the adequacy of the regression equation to the experiment. The critical value of the Student's criterion (t_{cris}=1.74) was used to identify statistically insignificant coefficients. The estimation of the statistically significant coefficients of the regression equation after removing the insignificant coefficients is presented in Table 7.

$$y_{AA}=-1.357\cdot10^4+2.975\cdot10^2\tau-25.470\tau^2+$$
$$+3.086\cdot10^2t-9.645t^2-5.023\cdot10^2w-5.980w^2. \quad (18)$$

Table 4

Evaluation of the coefficients of the regression equation expressing the dependence of SA on the parameters of the process of obtaining wheat malt

Complex of dimensionless variables	Corresponding dimensionless coefficients	Student's criterion value	Degree of significance of the coefficient	Complex of dimensional variables	Appropriate size coefficients
1	5.33	46.44	1	1	$-2.493 \cdot 10^{2}$
Z_0	–0.17	3.18	5	τ	5.109
Z_1	$6.28 \cdot 10^{2}$	1.18	6	W	9.568
Z_2	$-3.56 \cdot 10^{2}$	0.67	7	t	4.790
Z_0^2	–0.39	4.24	4	τ^2	–0.390
$Z_0 \cdot Z_1$	$-3.33 \cdot 10^{-2}$	0.51	8	$\tau \cdot W$	$-1.665 \cdot 10^{-2}$
$Z_0 \cdot Z_2$	$1.25 \cdot 10^{-2}$	0.19	9	$\tau \cdot t$	$6.259 \cdot 10^{-3}$
Z_1^2	–0.45	4.87	3	W^2	–0.113
$Z_1 \cdot Z_2$	$3.33 \cdot 10^{-2}$	$5.12 \cdot 10^{-2}$	10	$W \cdot t$	$8.33 \cdot 10^{-4}$
Z_2^2	–0.61	6.67	2	t^2	–0.153

Table 5

Evaluation of the coefficients of the regression equation expressing the dependence of SA on the parameters of the process of obtaining wheat malt, after removing statistically insignificant coefficients

Complex of dimensionless variables	Corresponding dimensionless coefficients	Student's criterion value	Degree of significance of the coefficient	Complex of dimensional variables	Appropriate size coefficients
1	5.33	49.78	1	1	$-2.452 \cdot 10^{3}$
Z_0	–0.17	3.41	5	τ	4.510
Z_0^2	–0.39	4.54	4	τ^2	–0.390
Z_1^2	–0.45	5.22	3	W^2	–0.113
Z_2^2	–0.61	7.15	2	t^2	–0.153
The coefficients are statistically insignificant				W	9.450
				T	4.880

Table 6

Evaluation of the coefficients of the regression equation expressing the dependence of AA on the parameters of the process of obtaining wheat malt

Complex of dimensionless variables	Corresponding dimensionless coefficients	Student's criterion value	Degree of significance of the coefficient	Complex of dimensional variables	Appropriate size coefficients
1	$3.19 \cdot 10^{2}$	45.07	1	1	$-1.376 \cdot 10^{4}$
Z_0	–8.19	2.50	5	τ	$3.180 \cdot 10^{2}$
Z_1	3.85	1.17	6	W	$5.113 \cdot 10^{2}$
Z_2	–3.77	1.15	7	t	$2.987 \cdot 10^{2}$
Z_0^2	–25.47	4.49	3	τ^2	–25.470
$Z_0 \cdot Z_1$	–2.17	0.54	9	$\tau \cdot w$	–1.085
$Z_0 \cdot Z_2$	3.13	0.78	8	$\tau \cdot t$	1.565
Z_1^2	–23.92	4.21	4	W^2	–5.980
$Z_1 \cdot Z_2$	–0.13	$3.11 \cdot 10^{-2}$	10	$W \cdot t$	$-3.25 \cdot 10^{-2}$
Z_2^2	–38.58	6.80	2	t^2	–9.645

Table 7

Evaluation of the coefficients of the regression equation expressing the dependence of AA on the parameters of the process of obtaining wheat malt after removing statistically insignificant coefficients

Complex of dimensionless variables	Corresponding dimensionless coefficients	Student's criterion value	Degree of significance of the coefficient	Complex of dimensional variables	Appropriate size coefficients
1	$3.19 \cdot 10^{2}$	45.07	1	1	$-1.357 \cdot 10^{4}$
Z_0	–8.19	2.58	5	τ	$2.975 \cdot 10^{2}$
Z_0^2	–25.47	4.64	3	τ^2	–25.470
Z_1^2	–23.92	4.35	4	W^2	–5.980
Z_2^2	–38.58	7.02	2	t^2	–9.645
Z_1	The coefficients are statistically insignificant			W	$5.023 \cdot 10^{2}$
Z_2				T	$3.086 \cdot 10^{2}$

Table 8

Minimum and maximum values of SA and AA in the optimization criterion during the optimization process of obtaining malt

Level of prices	Indexes	
	SA	AA
Min	3.69	221.5
Max	5.76	345.7

According to the regression model of the table, the largest value of AA corresponds to (320.0) τ=5.8 days, w=42.2 % and t=15.9 °C values. Its difference from the maximum experimental value (AA=345.7, τ=6 days, w=42 %, t=16 °C) is 7.4 %. The residual variance is estimated as $S_{var}^2=148(\mathrm{W-K})^2$, where ΔY_{AA} – 23.8 W-K units (Table 7).

According to this criterion, the optimization result of the wheat malt extraction process is as follows:

τ=5.8 days, w=42.2 %, t=15.9 °C; Y_{SA}=5.35, Y_{AA}=320.0.

The reported values were 7 % less than the maximum experimental values (Y_{SA}=5.76, Y_{AA}=345.7). A=1 was assumed during the optimization. The minimum and maximum values of the response functions were taken according to the experimental values (Table 8).

5. 2. Modeling and optimization of the germination process of barley malt

The process of obtaining barley malt has been modeled similarly to obtaining wheat malt. Variation limits of the factors for obtaining barley malt are given in Table 9.

Table 9

Variation limits of factors

Planning images	τ, per day	w, %	t, °C
Basic level, (0)	7	43	18
Variation interval, Δ	1	2	2
Level up (+1)	8	45	20
Low level (–1)	6	41	16

The planning matrix of the experiment in coded and dimensional values (three factors at three levels) is given in Table 10. The experiments at each point of the matrix have been repeated to increase the accuracy, and the number of parallel experiments is 3. Statistical criteria during the processing of experimental results: checking the homogeneity of variance of parallel experiments – Cochrane criterion, checking the significance of coefficients of the regression equation – Student's criterion, checking the adequacy of the regression equation – Fisher criterion. When testing all statistical hypotheses, the level of significance was accepted to be 0.95.

An equation that satisfies the hypothesis of adequacy was obtained as a result of statistical processing of the experimental values of Table 10 in the Match CAD 14 program according to the minimum criterion of the experimental and calculated root-mean-square deviation according to the significance model (the least squares model) (the reported value of the Fisher criterion F_{rep}=16.53 was higher than the table value F_{tab}=2.49 for AA). However, the error of approximating experimental values was up to 12 %.

Table 10

Planning and results of the experiment with barley malt

Experiment No.	Code symbol of factors			Size of factors			Y_{AA}, W-K units	Y_{SA}, units/g
	Z_0	Z_1	Z_2	τ, per day	w, %	t, °C		
1	–1	–1	–1	6	41	16	197.6	3.5
2	0	–1	–1	7	41	16	162.4	3.2
3	1	–1	–1	8	41	16	151.8	3.0
4	–1	0	–1	6	43	16	220.3	3.6
5	0	0	–1	7	43	16	215.8	3.8
6	1	0	–1	8	43	16	201.7	3.0
7	–1	1	–1	6	45	16	236.5	3.9
8	0	1	–1	7	45	16	225.4	3.8
9	1	1	–1	8	45	16	219.3	3.1
10	–1	–1	0	6	41	18	245.5	4.5
11	0	–1	0	7	41	18	228.1	4.5
12	1	–1	0	8	41	18	223.9	3.8
13	0	0	0	6	43	18	245.0	4.8
14	1	0	0	8	43	18	228.7	4.5
15	–1	0	0	8	43	18	224.7	4.0
16	–1	1	0	6	45	18	250.0	5.0
17	0	1	0	7	45	18	237.4	4.8
18	1	1	0	8	45	18	226.4	4.0
19	–1	–1	1	6	41	20	143.7	2.7
20	0	–1	1	7	41	20	125.6	2.6
21	1	–1	1	8	41	20	109.6	2.5
22	–1	0	1	6	43	20	185.4	2.8
23	0	0	1	7	43	20	173.7	2.8
24	1	0	1	8	43	20	165.4	2.8
25	–1	1	1	6	45	20	202.8	2.8
26	0	1	1	7	45	20	195.4	2.8
27	1	1	1	8	45	20	164.5	2.8

In addition, the optimal matching of the parameters proposed by this model is beyond what can be released due to the technology of the limits (Table 11).

The regression equation for saccharification ability (SA) also included cubic summands. Although the plan (design) of the experiment did not meet the orthogonal condition, it was possible to increase the adequacy of the model.

Table 11

Refinement results of the experiment on obtaining barley malt

Experiment No.	Code symbol of factors			Size of factors			Y_{AA}, W-K units	Y_{SA}, units/g
	Z_0	Z_1	Z_2	τ,per day	W, %	t, °C		
28	–2	1	–0.5	5	45	17	235.7	4.65
29	–2	1.5	–0.5	5	46	17	210.8	4.20
30	–2	1	0	5	45	18	238.4	4.60
31	–2	1.5	0	5	46	18	213.4	4.22
32	–1	1.5	–0.5	6	46	17	209.4	4.48
33	–1	1.5	0	6	46	18	216.8	4.53

The evaluation of the statistically insignificant coefficients of the regression equations before their exclusion from the equation is given in Tables 12, 14 and after their exclusion in Tables 13, 15. In order to evaluate the degree of influence of each factor, the ranks (levels) of the coefficients of the regression equation determined according to the corresponding Student's criterion value are shown in the tables: rank 1 has been attributed to the dimensionless complex with the greatest significance with the highest Student's criterion value, and rank 13 to the complex with the smallest Student's criterion value.

The reported value of the Fisher criterion H_{rep}=62.47 has been obtained higher than the table value F_{tab}=2.28 (27 times). This makes it possible to accept the hypothesis about the adequacy of the regression equation to the experiment. The critical value of the Student's criterion is F_{crit}=1.71. Thus, the regression equation that adequately expresses the dependence of saccharification ability (SA) on the parameters of the process of obtaining barley malt and free of insignificant coefficients is as follows:

$$Y_{SA}=1.940\cdot10^3+0.684\tau-0.162\tau^2+ +11.52t-0.339t^2+7.35\cdot10^{-2}\tau t-1.427\cdot10^2w- -3.322W^2+2.58\cdot10^2\ W^3. \quad (19)$$

The equation is given in variable dimensions, which, in contrast to the dimensionless form of the equation, allows us not only to analyze the effect of the input parameters, but also to predict the value of the response function within the released limits. Residual dispersion is evaluated with the value $S^2_{res}=0.017$ (unit/g). At this time (without verification), assuming a normal distribution of random error deviation, we use the following formula to calculate the uncertainty of the model (3):

$$\Delta Y_{SA}=t\cdot\sqrt{S^2_{res}}. \quad (20)$$

Here t=1.96 is the Student's criterion value with an infinitely high degree of freedom at a confidence probability of 0.95. Therefore, Y_{SA}=0.26 units/g.

According to Table 13, the greatest SA value of the regression model is 4.94, other parameters are τ=6.1 days, w=44.5 %, t=17.6 °C.

The reported value of the Fisher criterion F_{rep}=16.45 was obtained higher (7.1 times) than the table value F_{tab}=2.32. This gives reason to accept the hypothesis about the adequacy of the regression equation to the experiment. The critical value of the Student's criterion is t_{crit}=1.72 and after removing the insignificant coefficients, the evaluation of the statistically significant coefficients of the regression equation is presented in Table 15.

The reported value of the Fisher criterion F_{rep}=25.83 was higher (10.4 times) than its table value F_{tab}=2.47. This allows us to accept the hypothesis about the adequacy of the regression equation to the experiment. The critical value of the Student's criterion is t_{crit}=1.71. Thus, it can be said that the regression equation with dimensional values adequately reflects the dependence of amylolytic activity (AA) on barley malt germination parameters. After removing statistically insignificant coefficients, the regression equation can be written as follows:

$$Y_{AA}=1.094\cdot10^4-2.041\cdot10\tau+4.519\tau w+ +4.187\cdot10^2t-11.90t^2+3.74910^2w- -4.627W^2. \quad (21)$$

According to the regression model, the highest value of amylolytic activity is 256.8. The corresponding values of the parameters are as follows: τ=5.7 days, w=43.7 %, t=17.6 °C. The difference from the maximum experimental value (6 days, 45 % and 250.0 at 18 °C) was +2.7 %.

Table 12

Evaluation of the coefficients of the regression equation expressing the dependence of saccharifying ability on the barley malt malting parameter

Complex of dimensionless variables	Corresponding dimensionless coefficients	Student's criterion value	Degree of significance of the coefficient	Complex of dimensional variables	Appropriate size coefficients
1 (independent variables)	4.581	55.94	1	1 (independent variables)	$1.849\cdot10^3$
Z_0	−0.273	4.40	3	τ	3.295
Z_1	0.364	3.63	4	w	$-1.435\cdot10^2$
Z_2	0.464	1.29	8	t	25.81
Z_0^2	−0.162	2.47	6	τ^2	−0.414
$Z_0\cdot Z_1$	−0.037	0.80	10	$\tau\cdot w$	$-1.85\cdot10^{-2}$
$Z_0\cdot Z_2$	0.140	3.03	5	$\tau\cdot t$	$7.00\cdot10^{-2}$
Z_1^2	−0.045	0.69	11	W^2	3.359
$Z_1\cdot Z_2$	−0.041	0.88	9	wt	$-1.03\cdot10^{-2}$
Z_2^2	−1.360	21.08	2	t^2	−1.110
Z_0^3	0.012	0.29	13	τ^3	$1.20\cdot10^{-2}$
Z_1^3	−0.209	2.46	7	W^3	$-2.6\cdot10^{-2}$
Z_2^3	0.114	0.31	12	t^3	$1.43\cdot10^{-2}$

Table 13

Evaluation of the coefficients of the regression equation expressing the dependence of saccharification ability (SA) on the parameters of the process of obtaining barley malt after removing the statistically insignificant coefficients

Complex of dimensionless variables	Corresponding dimensionless coefficients	Student's criterion value	Degree of significance of the coefficient	Complex of dimensional variables	Appropriate size coefficients
1	4.550	80.27	1	1	$1.940\cdot10^3$
Z_0	−0.261	7.64	4	τ	0.684
Z_1	0.362	4.80	6	w	$-1.427\cdot10^2$
Z_2	−0.353	9.8	3	T	11.52
Z_0^2	−0.162	5.31	5	τ^2	−0.162
$Z_0\cdot Z_2$	0.147	3.53	8	$\tau\cdot t$	$7.35\cdot10^{-2}$
Z_2^2	−1.357	22.47	2	t^2	−0.339
Z_1^3	−0.206	3.75	7	W^3	$-2.58\cdot10^{-2}$
Z_1^2	The coefficients are statistically insignificant			W^2	3.332

made it possible to determine a number of insignificant coefficients. The condition after removing insignificant coefficients is the same as in Table 13.

The reported value of the Fisher criterion F_{rep}=102.53 has been obtained higher (50 times) than the table value F_{tab}=2.41. The critical value of the Student's criterion

Table 14

Evaluation of the coefficients of the regression equation expressing the dependence of saccharification ability on the parameters of the barley malt production process

Complex of dimensionless variables	Corresponding dimensionless coefficients	Student's criterion value	Degree of significance of the coefficient	Complex of dimensional variables	Appropriate size coefficients
1	245.81	34.75	1	1	$1.076 \cdot 10^4$
Z_0	–11.10	3.16	6	τ	$-1.944 \cdot 10^2$
Z_1	17.79	5.08	4	w	$3.707 \cdot 10^2$
Z_2	–19.83	5.46	3	T	$4.05 \cdot 10^2$
Z_0^2	–3.60	1.00	8	$\tau \cdot w$	3.596
$Z_0 \cdot Z_1$	6.85	1.72	7	$\tau \cdot t$	3.424
$Z_0 \cdot Z_2$	–1.58	0.37	10	W^2	–0.792
Z_1^2	–18.40	3.65	5	t^2	–4.60
$Z_1 \cdot Z_2$	2.19	0.50	9	$w \cdot t$	0.547
Z_2^2	–48.19	7.80	2	t^2	–12.04

Table 15

Evaluation of the coefficients of the regression equation expressing the dependence of saccharification ability (SA) on the parameters of the process of obtaining barley malt after excluding statistically insignificant coefficients

Complex of dimensionless variables	Corresponding dimensionless coefficients	Student's criterion value	Degree of significance of the coefficient	Complex of dimensional variables	Appropriate size coefficients
1	242.77	39.46	1	1	$1.094 \cdot 10^4$
Z_0	–9.75	3.04	6	τ	$-2.041 \cdot 10^2$
Z_1	17.37	5.13	4	w	$3.749 \cdot 10^2$
Z_2	–19.60	5.57	3	t	$4.189 \cdot 10^2$
Z_0Z_1	9.04	2.67	7	$\tau\, w$	4.519
Z_1^2	–18.51	3.78	5	w^2	–4.627
Z_2^2	–47.61	7.98	2	t^2	–11.90

The value of residual dispersion is S^2=180.1 (W-K) units. Here (W-K) is the Windisch-Kolbach unit.

The optimization according to the compromise criterion between the maximum values of the saccharifying ability and amylolytic activity of the barley malt germination process is as follows:

$$J = \frac{Y_{SA}(\tau,w,t) - Y_{SA\min}}{Y_{SA\max} - Y_{SA\min}} + A\frac{Y_{AA}(\tau,w,t) - Y_{AA\min}}{Y_{SA\max} - Y_{SA\min}}. \quad (22)$$

Here A – weighting factor.

Table 16

Maximum and minimum values of saccharification ability and amylolytic activity during the optimization of the germination process of barley malt

Coefficient	SA	AA
Min	2.5	109.6
Max	5.0	250

The obtained results are as follows: τ=6.1 days; w=44.1 %; t=17.6 °C; Y_{SA}=4.93; Y_{AA}=255.2. A=1 was accepted during the optimization.

5. 3. Modeling and optimization of the germination process of rye malt

Modeling and optimization of the process of obtaining rye malt were performed similarly to modeling and optimization of the germination process of wheat and barley. The variation limits of the plan factors are given in Table 17.

Table 17

Limits of variation of active experimental factors for obtaining rye malt

Planning images	τ, per day	w, %	t, °C
Basic level, (0)	4	44	16
Variation interval, Δ	1	2	2
Level up (+1)	5	46	18
Low level (–1)	3	42	14

The planning matrix of the experiment is given in Table 18. According to the experimental values of this table, quadratic regression equations have been obtained for approximating the saccharification ability (SA) and amylolytic activity (AA) values of rye malt using the least squares method.

The adequacy of equations to regression analysis methods was checked by the Fisher criterion, the statistical significance of their coefficients by the Student's criterion, the homogeneity of parallel experiments was checked by the Cochrane criterion. The evaluation of regression coefficients before the removal of statistically insignificant coefficients is given in Tables 19, 21, and after the removal of statistical coefficients in Tables 20, 22,

The reported value of the Fisher criterion F_{rep}=26.64 was higher (10.7 times) than its table value F_{tab}=2.49. This gives grounds for accepting the hypothesis about the adequacy of the regression equation to the experiment. The critical value of the Student's criterion t_{crit}=1.74 made it possible to identify statistically insignificant coefficients. The evaluation of the statistically significant coefficients of the regression equation is given in Table 22, after removing the insignificant coefficients.

The reported value of the Fisher criterion F_{rep}=34.27 was higher (13.5 times) than its table value F_{tab}=2.54. This gives grounds for accepting the hypothesis about the adequacy of the regression equation to the experiment. The critical value of the Student's criterion is t_{crit}=1.73. Thus, the regression equation showing the dependence of saccharification ability (SA) on the parameters of the rye malt growing process is as follows after removing the statistically insignificant coefficients:

$$Y_{SA}=1.035\cdot10^{2}+4.450\tau-0.350\tau^{2}+ +4.070t-0.123t^{2}-8.500\cdot10^{-2}+ +\tau\cdot t+2.915w-3.25010^{-2}W^{2}. \quad (23)$$

Table 18

Rye malt obtaining planning matrix and experiment results

Experiment No.	Code symbol of factors			Size of factors			Y_{AA}, W-K units	Y_{SA}, units/g
	Z_0	Z_1	Z_2	τ, per day	w, %	t, °C		
1	–1	–1	–1	3	42	14	101.6	1.35
2	0	–1	–1	4	42	14	159.5	2.13
3	1	–1	–1	5	42	14	144.3	1.92
4	–1	0	–1	3	44	14	113.2	1.51
5	0	0	–1	4	44	14	178.5	2.38
6	1	0	–1	5	44	14	171.8	2.29
7	–1	1	–1	3	46	14	108.2	1.44
8	0	1	–1	4	46	14	181.4	2.42
9	1	1	–1	5	46	14	175.5	2.34
10	–1	–1	0	3	42	16	102.7	1.37
11	0	–1	0	4	42	16	162.8	2.17
12	1	–1	0	5	42	16	160.4	2.14
13	0	0	0	3	44	16	115.8	1.54
14	1	0	0	4	44	16	196.4	2.49
15	–1	0	0	5	44	16	192.6	2.57
16	–1	1	0	3	46	16	111.4	1.49
17	0	1	0	4	46	16	189.3	2.52
18	1	1	0	5	46	16	185.4	2.47
19	–1	–1	1	3	42	18	75.4	1.10
20	0	–1	1	4	42	18	88.6	1.18
21	1	–1	1	5	42	18	80.4	1.07
22	–1	0	1	3	44	18	89.2	1.19
23	0	0	1	4	44	18	99.8	1.33
24	1	0	1	5	44	18	97.2	1.29
25	–1	1	1	3	46	18	86.3	1.15
26	0	1	1	4	46	18	98.7	1.32
27	1	1	1	5	46	18	96.3	1.28

Table 19

Evaluation of the coefficient of the regression equation expressing the dependence of saccharification ability on the parameters of the process of obtaining rye malt

Complex of dimensionless variables	Corresponding dimensionless coefficients	Student's criterion value	Degree of significance of the coefficient	Complex of dimensional variables	Appropriate size coefficients
1	2.41	27.53	1	1	$-1.042\cdot10^{2}$
Z_0	0.29	7.18	3	τ	3.157
Z_1	0.11	2.75	7	w	2.932
Z_2	–0.38	9.43	2	t	4.436
Z_0^2	–0.35	5.05	5	τ^2	–0.350
Z_0Z_1	$5.83\cdot10^{-2}$	1.18	9	$\tau\cdot w$	$2.915\cdot10^{-2}$
Z_0Z_2	–0.17	3.45	6	$\tau\cdot t$	$-8.500\cdot10^{-2}$
Z_1^2	–0.13	1.84	8	W^2	$-3.250\cdot10^{-2}$
Z_1Z_2	$-3.33\cdot10^{-2}$	0.67	10	$w\cdot\tau$	$-8.325\cdot10^{-3}$
Z_2^2	–0.49	7.00	4	t^2	–0.123

Table 20

Estimation of the coefficients of the regression equation reflecting the dependence of saccharification ability on the parameters of the process of obtaining rye malt after removing the statistically insignificant coefficients

Complex of dimensionless variables	Corresponding dimensionless coefficients	Student's criterion value	Degree of significance of the coefficient	Complex of dimensional variables	Appropriate size coefficients
1	2.41	27.56	1	1	$-1.035 \cdot 10^2$
Z_0	0.29	7.21	3	τ	4.450
Z_1	0.11	2.76	7	W	2.915
Z_2	–0.38	9.47	2	T	4.070
Z_0^2	–0.35	5.07	5	τ^2	–0.350
Z_0Z_2	–0.17	3.46	6	$\tau \cdot t$	$8.500 \cdot 10^{-2}$
Z_1^2	–0.49	1.85	8	W^2	$-3.250 \cdot 10^{-2}$
Z_2^2	–0.49	7.03	4	t^2	–0.123

Table 21

Evaluation of the coefficients of the regression equation expressing the dependence of amylolytic activity on the parameters of the process of obtaining rye malt

Complex of dimensionless variables	Corresponding dimensionless coefficients	Student's criterion value	Degree of significance of the coefficient	Complex of dimensional variables	Appropriate size coefficients
1	$1.83 \cdot 10^2$	27.97	1	1	$-7.877 \cdot 10^3$
Z_0	22.23	7.12	3	τ	$2.585 \cdot 10^2$
Z_1	8.87	2.87	7	W	$2.346 \cdot 10^2$
Z_2	–29.01	9.55	2	T	$2.945 \cdot 10^2$
Z_0^2	–27.91	5.31	5	τ^2	–27.91
Z_0Z_1	3.82	1.03	9	$\tau \cdot w$	1.910
Z_0Z_2	–12.13	3.26	6	$\tau \cdot t$	–6.065
Z_1^2	–11.16	2.12	8	W^2	–2.790
Z_1Z_2	–1.9	0.51	10	$w \cdot \tau$	0.475
Z_2^2	–38.21	7.26	4	t^2	–9.553

Table 22

Evaluation of the coefficients of the regression equation expressing the dependence of amylolytic activity on the parameters of the process of obtaining rye malt after removing statistically insignificant coefficients

Complex of dimensionless variables	Corresponding dimensionless coefficients	Student's criterion value	Degree of significance of the coefficient	Complex of dimensional variables	Appropriate size coefficients
1	$1.83 \cdot 10^2$	27.97	1	1	$-8.547 \cdot 10^2$
Z_0	22.23	7.32	3	τ	$3.426 \cdot 10^2$
Z_1	8.87	2.87	7	W	$2.499 \cdot 10^2$
Z_2	–29.01	9.55	2	T	$3.154 \cdot 10^2$
Z_0^2	–27.91	5.31	5	τ^2	–27.91
Z_0Z_2	–12.13	3.26	6	$\tau \cdot t$	–6.065
Z_1^2	–11.16	2.12	8	W^2	–2.790
Z_2^2	–38.21	7.26	4	t^2	–9.553

According to the regression model in Table 21, the highest value of saccharification ability is 2.63. And the corresponding parameters are: τ=4.6 days, w=45.2 %, t=15.0 °C. The normal difference from the experimental value is +2.2 %. Here the residual dispersion is $S^2_{res}=0.021$ units/g. Whereas, according to Table 20, ΔY_{SA}=0.28 unit/g.

The reported value of the Fisher criterion F_{rep}=36.92 was obtained higher (14.51 times) than its table value F_{tab}=2.54 (Table 22). This gives reason to accept the hypothesis that the regression equation is adequate for the experiment. The critical value of the Student's criterion is t_{crit}=1.73, thus the form of the dimensional regression equation expressing the dependence of the amylolytic activity of rye malt on the growing parameters after removing the statistically insignificant coefficients is as follows:

$$Y_{AA}=-8.547 \cdot 10^3+3.426 \cdot 10^2\tau-27.91\tau^2+3.154,$$

$$\tau-9.553 \cdot t^2-6.065\tau-2.499 \cdot 10^2 w-2.790 w^2. \quad (24)$$

According to the regression model, τ=4.5 days, w=45.1 %, t=15.0 °C. The highest value of amylolytic activity in its parameters is 198.2. The deviation from the maximum experimental value (4 days, 44 %, 196.4 at

16 °C) is +0.9 %. The residual variance is evaluated with S^2_{res} =113 (W–K)^2 units. Whereas, Y_{AA}=208 (W–K) units.

The results of the optimization process for growing rye malt are as follows: τ=4.6 days; *w*=45.1 %; *t*=15.0 °C; Y_{SA}=2.63; during optimization *A*=1, the minimum and maximum values of the response function (*y*) were selected according to the experimental data given in Table 23.

Table 23

Minimum and maximum values of saccharification ability and amylolytic activity in the process of obtaining rye malt

Coefficient	SA	AA
Min	1.07	75.4
Max	2.57	196.4

In practice, 2 main options are used when making saccharified juice in distillate production depending on the ratio in the composition of malted and unmalted grain raw materials. The special feature in the first case is that enzymatic catalysis of hydrolytic processes takes place under the influence of malt's own enzyme. This is the same as in the preparation of beer juice. Here, the amylolytic (AA) and saccharification (SA) activity of malt provides the normative extract value of juice. In the second case, when a grain communal composition containing 20–25 % non-malted materials is selected, there is a need to use amylolytic and cytolytic microbial enzyme preparations.

Taking into consideration the raw material characteristics of wheat, barley and rye malt (quantity of germination ability), the first option is practically more favorable.

Data on the optimization of the process of obtaining malt is given in Table 24.

Table 24

Final data on the optimization of the process of obtaining malt

Grain type	Barley	Wheat	Rye
Optimum values of influencing factors			
Germination period, days	6.1	5.8	4.6
Wetting degree, %	44.1	42.2	45.1
Germination temperature, °C	17.6	15.9	15.0
Reported value of the quality criterion of malt			
SA, units/g	4.93	5.35	8.63
AA, W-K units	255.2	320.0	198.1

As can be seen from the table, grains differ from each other in terms of germination time, wetting degree and germination temperature. Thus, the highest germination period is observed in barley – 6.1 days, and the lowest in rye – 4.6 days. Rye has a high wetting rate of 45.1 %, but it germinates at the lowest temperature –15 °C. Compared to other samples, barley germinates at a higher temperature –17.6 °C.

5. 4. Study of the temperature dependence of the amylolytic activity and saccharification ability of the enzymatic complex of barley, wheat and rye malts

Fig. 1 shows the temperature dependence of AA and SA for barley malt. These demonstrate that the reported results with regression equations are little different from the experimental values (points) before and after removing the statically insignificant coefficients (curves 1 and 2).

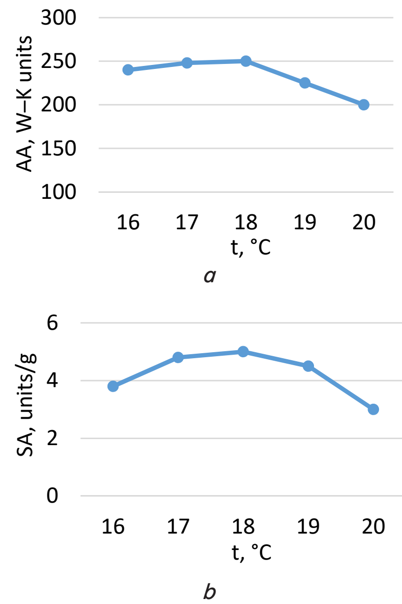


Fig. 1. Dependence of the AA and SA indicators of barley malt on temperature: *a* – the temperature dependence of the amylolytic activity of barley malt; *b* – the temperature dependence of the saccharifying activity of barley malt (τ=6 days; *W*=45 %)

Fig. 2–4 show the reported results obtained by regression equations with statically insignificant coefficients (not removed) for all studied malt varieties (1 – barley, 2 – wheat, 3 – rye). Reported values are compared with experimental values (o – barley, ◊ – wheat, □ – rye).

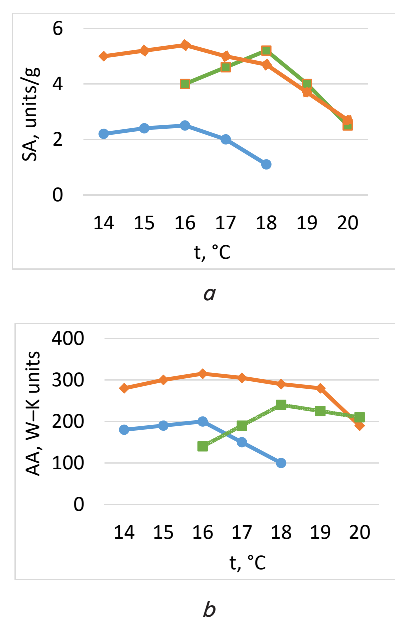
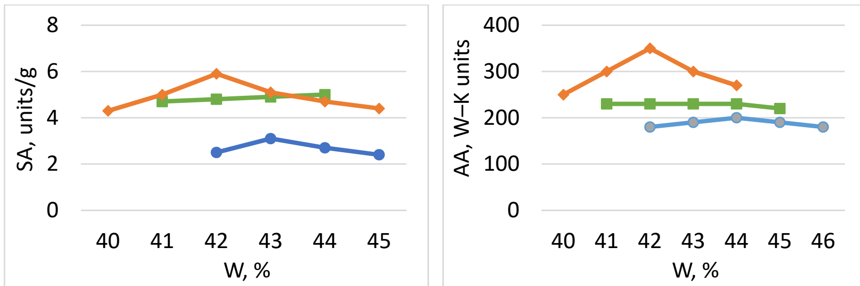
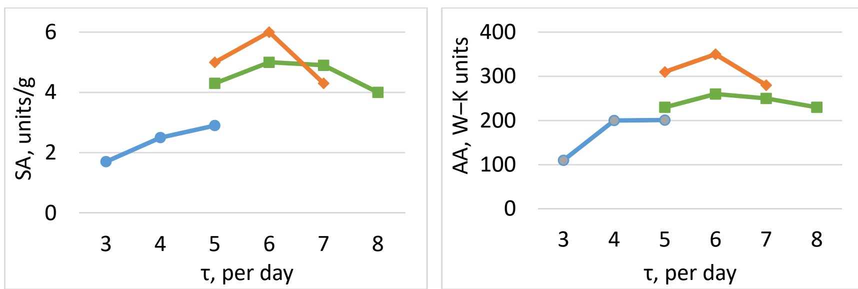


Fig. 2. Dependence of the AA and SA parameters of the studied malts on temperature: *a* – dependence of the saccharifying activity parameters of the studied malts on temperature; *b* – dependence of the amylolytic activity of the studied malts on temperature: (τ=6 days; *W*=45 % – barley), (τ=6 days; *W*=42 % – wheat), (τ=5 days, *W*=44 % with rye): experimental points: o – barley, ◊ – wheat, □ – rye



a *b*

Fig. 3. Dependence of the AA and SA indicators of the studied malts on wetting degree: *a* – dependence of the saccharifying activity indicators of the studied malts on wetting degree; *b* – dependence of the amylolytic activity indicators of the studied malts on wetting degree. (τ=6 days; *t*=16 °C – rye): experimental points: o – barley, ◊ – wheat, □ – rye



a *b*

Fig. 4. Dependence of the AA and SA indicators of the studied malts on germination period: *a* – dependence of the saccharifying activity indicators of the studied malts on germination period; *b* – dependence of the amylolytic activity indicators of the studied malts on germination period (*w*=45 %; *t*=18 °C – barley); (*w*=42 %; *t*=16 °C – wheat); (*w*=44 %; *t*=16 °C – rye): experimental points: o – barley; ◊ – wheat; □ – rye

The analysis of the obtained dependencies shows that the germination temperature of barley, wheat and rye has the maximum effect on the complex of amylolytic enzymes of malts.

6. Discussion of the results of modeling and optimization of the process of obtaining malt from barley, wheat and rye

Thus, during the modeling and optimization of the wheat, barley and rye malt breeding process, the effect of factors such as germination time, wetting degree and temperature on the amylolytic activity (AA) and saccharification ability (SA) of the malt enzymatic complex was studied. The following features emerged during the study.

The saccharifying ability (SA) of wheat and barley malts is mostly affected by the germination temperature, secondly by the wetting degree, and thirdly by the germination period (Table 3). The influence of these three factors on the quantity of saccharifying ability (SA) is not linear, which is shown by the high value of the Student's criterion for coefficients with quadratic thresholds (critical value of the Student's criterion: t_{crit}=1.72 for wheat, t_{crit}=1.71 for barley). It should be noted that none of the coefficients responsible for the joint effect of the factors was statistically significant, and the effect on the amount of saccharification ability (SA) was insignificant. If we look at the dependence of the saccharification ability on the parameters of the barley malt production process, the greatest value of the regression model is 4.94, other parameters are τ=6.1 days, *w*=44.5 %, *t*=17.6 °C (Table 14).

Completely different results were obtained for the effect of the factors applied during obtaining rye malt on the saccharification ability. It was determined that the malt saccharification ability (SA) is most affected by the germination period, secondly by the germination temperature, and thirdly by the wetting degree. Unlike barley malt, the saccharifying ability of rye malt is significantly influenced by germination temperature and time (Table 18). The effect of wetting degree on the saccharification ability of rye malt is close to statistical insignificance and lags behind the joint effect of temperature and germination period. The non-linear effect of temperature and germination period on the saccharification ability cannot be ignored. This is evidenced by the Student's criterion values in the corresponding quadratic summands.

Different results were obtained for the influence of the investigated factors on the amylolytic activity (AF) of wheat and barley malts. The amylolytic activity (AF) of wheat malt is more affected by the germination temperature, secondly by the germination time, and thirdly by the wetting degree. The effect of all three factors on the AA quantity is not linear, as evidenced by the high value of the Student's criterion for the coefficients with the presence of quadratic thresholds. At the same time, none of the coefficients responsible for the joint effect of the factors was statistically significant, indicating that they have a slight effect. The latter two deviations are also related to the SA quantity of wheat malt.

The amount of amylolytic activity (AA), such as saccharification ability (SA) of barley malt, is more affected by germination temperature, secondly by wetting degree, and thirdly by germination time. The effect of temperature on amylolytic activity (AA) and saccharification ability (SA) is not linear. This is also proved by the fact that the Student's coefficient for the t^2 coefficient is an integer. However, the effect of temperature on saccharification ability is greater than on amylolytic activity. Among the coefficients indicating the joint effect of the factors, the statistically significant ones are the germination period and wetting degree.

During the research, it was determined that the germination temperature most affects the amylolytic activity value of rye malt. From this point of view, the second place is the germination period and the third place is the wetting degree. As for saccharification ability, the joint effect of temperature and germination time on amylolytic activity is greater than the effect of wetting degree. Here, the non-linear nature of the joint effect of temperature and germination period factors should not be overlooked.

The study of the dependence of the amylolytic activity and saccharification ability of the enzymatic complex of barley, wheat, and rye malts on temperature shows that the germination temperature of barley, wheat, and rye has the maximum effect on the complex of amylolytic enzymes of malts.

Compared to traditional one-dimensional methods, the multivariate analysis used in malt production gave complete information, since it allowed investigating various factors of malt fermentation.

Because the influence of different values and combinations of factors such as germination time, germination temperature and wetting degree can lead to different results. However, the methodology we chose allowed us to more broadly study the influence of such factors as germination time, wetting degree and germination temperature on the quality of malt obtained from wheat, barley and rye. In addition, we studied the dependence of the amylolytic activity (AA) and saccharification ability (SA) of the enzymatic complex of barley, wheat and rye malt on temperature.

Further development of our research consists in obtaining beverage concentrates based on plant raw materials with biologically active properties with liquid and powdered malt extract and powdered polymalt extract from wheat, barley and rye.

7. Conclusions

1. The optimal values of influencing factors during the study of the optimization of the process of obtaining barley malt are as follows: germination period – 6.1 days, wetting degree – 44.1 %, germination temperature – 17.6 °C. Whereas, the quality criterion of malt was the saccharification ability (SA) – 4.93 units/g, amylolytic activity – 255.2 W-K units.

2. The optimal values of the influencing factors during the study of the optimization of the process of obtaining wheat malt are as follows: germination period – 5.8 days, wetting degree – 42.2 %, germination temperature – 15.9 °C. Whereas, the quality criterion of malt was the saccharification ability (SA) – 5.35 units/g, amylolytic activity – 320.0 W-K units.

3. The optimal values of influencing factors during the study of the optimization of the process of obtaining rye malt are as follows: germination period – 4.6 days, wetting degree – 45.1 %, germination temperature – 15.0 °C. Whereas, the quality criterion of malt was the saccharification ability (SA) – 8.63 units/g, amylolytic activity – 198.1 W-K units.

4. The temperature dependence of the amylolytic activity and saccharifying ability of malts is not linear. Barley malt (τ=6 days; w=45 %) exhibits the highest amylolytic activity and saccharifying ability at 15 °C. Wheat malt (τ=6 days; w=42 %) exhibits the highest amylolytic activity and saccharifying ability at 16 °C. Rye malt (τ=5 days; w=44 %) exhibits the highest amylolytic activity and saccharifying ability at 17.5 °C.

Conflict of interest

We, the authors, declare that we have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

Financing

The study was performed without financial support.

Data availability

Data will be made available on reasonable request.

References

1. Patra, M., Bashir, O., Amin, T., Wani, A. W., Shams, R., Chaudhary, K. S. et al. (2023). A comprehensive review on functional beverages from cereal grains-characterization of nutraceutical potential, processing technologies and product types. Heliyon, 9 (6), e16804. doi: https://doi.org/10.1016/j.heliyon.2023.e16804
2. Almaguer, C., Kollmannsberger, H., Gastl, M., Becker, T. (2023). Comparative study of the impact of malting on the aroma profiles of barley (Hordeum vulgare L.) and rye (Secale cereale L.). Food Chemistry, 427, 136694. doi: https://doi.org/10.1016/j.foodchem.2023.136694
3. Panigrahi, C., Mishra, H. N., De, S. (2022). Ozone treatment of ultrafiltered sugarcane juice: Process optimization using multi-objective genetic algorithm and correlation analysis by multivariate technique. LWT, 154, 112861. doi: https://doi.org/10.1016/j.lwt.2021.112861
4. Calvi, A., Preiti, G., Gastl, M., Poiana, M., Zarnkow, M. (2023). Malting process optimization of an Italian common wheat landrace (Triticum aestivum L.) through response surface methodology and desirability approach. LWT, 173, 114242. doi: https://doi.org/10.1016/j.lwt.2022.114242
5. Muñoz-Insa, A., Selciano, H., Zarnkow, M., Becker, T., Gastl, M. (2013). Malting process optimization of spelt (Triticum spelta L.) for the brewing process. LWT - Food Science and Technology, 50 (1), 99–109. doi: https://doi.org/10.1016/j.lwt.2012.06.019
6. Tene, S. T., Ndinteh, D. T., Dongmo, J. R., Adebo, O. A., Kewuyemi, Y. O., Kengne Kamdem, M. H. et al. (2022). Optimization using response surface methodology of amylolytic capacity of maize Atp-Y and coca-sr varieties: In vitro digestibility capacity, physico-chemical and functional properties of optimal sample. Journal of Agriculture and Food Research, 9, 100342. doi: https://doi.org/10.1016/j.jafr.2022.100342
7. Soares, M. A. B., Jorge, L. M. De M., Montanuci, F. D. (2016). Drying kinetics of barley grains and effects on the germination index. Food Science and Technology, 36 (4), 638–645. doi: https://doi.org/10.1590/1678-457x.11916

8. Kaur, K. T., Kaur, J. T., Kaur, A. T. (2021). Current Trends in Multigrain Foods for Healthcare. Cereals and Cereal-Based Foods, 83–99. doi: https://doi.org/10.1201/9781003081975-7
9. Gadimova, N., Fataliyev, H., Allahverdiyeva, Z., Musayev, T., Akhundova, N., Babashli, A. (2022). Obtaining and investigation of the chemical composition of powdered malt and polymalt extracts for application in the production of non-alcoholic functional beverages. Eastern-European Journal of Enterprise Technologies, 5 (11 (119)), 66–74. doi: https://doi.org/10.15587/1729-4061.2022.265762
10. Thakur, A., Pandey, P., Dalbhagat, C. G., Mishra, H. N. (2021). Development of grain-based carbonated beverage premix using maize (Zea Mays), Bengal gram (Cicer Arietinum), and finger millet (Eleusine Coracana). Journal of Food Science and Technology, 59 (4), 1637–1648. doi: https://doi.org/10.1007/s13197-021-05175-5
11. Estevão, S. T., Batista de Almeida e Silva, J., Louren o, F. R. (2021). Development and optimization of beer containing malted and non-malted substitutes using quality by design (QbD) approach. Journal of Food Engineering, 289, 110182. doi: https://doi.org/10.1016/j.jfoodeng.2020.110182