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PLANT GROWING, PLANT PROTECTION AND BIOTECHNOLOGY

Research Techniques for the Quality of Wholemeal Rye Flour

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Abstract—Research was carried out to evaluate the indicators determining the baking, functional, and technological properties and to identify correlations between these parameters in wholemeal rye flour. Using different evaluation methods, the authors determined 18 parameters of baking and rheological properties in ten Russian varieties of winter rye. In addition, the characteristics of the swelling curve were measured using an Amylograph Brabender at 30°C, and the water extract viscosity (VWE) and the content of water-soluble pentosans and protein were evaluated. A high correlation was found between maximum swelling after incubation at 30°C for 30 min, with the falling number (r = 0.85), amylogram peak viscosity (r = 0.90) and VWE (r = 0.94), and between VWE and gelatinization temperature (r = 0.72) and the falling number (r = 0.82). The most significant indicators for inclusion in breeding programs for baking and fodder varieties of winter rye are falling number, water extract viscosity, swelling rate, protein content, water-soluble pentosan content, water-absorption capacity, dough stability, and farinograph quality number. In the early stages of selection, only four characteristics can be limited for the evaluation of wholemeal flours: the falling number, swelling rate, water extract viscosity, and the farinograph quality number. The principal component analysis also demonstrated that there are reliable differences between the rye varieties under study in terms of the set of traits that characterize their raw material value.

Keywords: winter rye (*Secale cereale* L.), wholemeal flour, dough, amylograph, farinograph, viscosity, falling number, swelling, gelatinization

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INTRODUCTION

Rye is one of the most important cereal crops of traditional importance in the nutrition of the population of the Earth's northern hemisphere. It plays an important agronomic, nutritional, and social role throughout the history of human civilization [1].

Winter rye is of particular importance in conditions of climatic anomalies (frosty winters and extremely dry summer months) as an insurance crop and the most resistant to abiotic stress factors [2, 3]. Its agrotechnical role in adaptive landscape agriculture is primarily associated with minimizing production costs, especially in regions with marginal soils.

The sown areas and gross yields of rye grain in the Russian Federation over the past decade have significantly decreased down to a record low (846 thousand ha) in 2019, when the country experienced a shortage of grain of this crop with the lowest production (1.43 million tonnes).

The creation of a sustainable market for rye grain in the country will largely be associated with the development of industries, such as poultry and pig farming, since grain makes up a significant part of the feed resources in animal husbandry.

The main chemical components of rye grains are the same as those of other cereals: protein, carbohydrates, minerals, and vitamins. Carbohydrates in rye flour are represented by starch and nonstarch heteropolysaccharides, which are often referred to in the specialized literature as pentosans or arabinoxylans (AX). According to various sources, rye grain contains from 2.5 to 12.2% of AX from dry matter, compared with 6–7% in wheat [4]. Arabinoxylans are usually categorized as dietary fibers.

With a close total amount of pentosans, the content of their water-soluble fraction in rye grain is approximately two times higher than in wheat. Winter rye contains 73% of insoluble dietary fiber, and the proportion of soluble fiber is 27% [5].

The steady interest in the study of rye AX is stimulated by many functional properties that characterize them. With regard to human health, AX have a positive effect on the intestinal activity and metabolism, as well as on the quantity, quality, and composition of the intestinal microflora. The nutritional benefits of high rye consumption include a positive effect on digestion and a reduction in the risk of heart disease, hypercholesterolemia, obesity, and non-insulin-dependent diabetes mellitus as well as a protective effect against certain hormone-dependent cancers [6].

Rye flour with good baking qualities should be characterized by a high content of AX as well as a high proportion of water-soluble fraction, which positively affects the volume, shape stability, structure of the crumb of rye bread, and slows down its hardening [7]. The baking potential of rye flour can be increased by using pentosans as dough-forming ingredients [8].

At the same time, the high content of high-molecular soluble pentosans is a significant obstacle to the use of rye grain for fodder purposes.

The antinutritional properties of pentosans are caused by their significant hydrophilicity; as a result, when dissolved in water, due to their large molecular weight, they form hydrocolloids with high viscosity.

Therefore, significant amounts of rye introduced into the diet leads to indigestion and decreased digestibility of nutrients in animals. Rye grain also contains enzymes, in particular amylases, that decompose starch and play a key role in determining the baking qualities of flour [9].

To determine the quality characteristics of wholemeal flour, various methods and appropriate equipment are used. The quality of starch and the activity of α-amylase determine the values of the falling number (FN) and the amylogram height [10]. The parameters of the maximum viscosity of the rye suspension and the temperature at which it is reached, which is in the range from 62 to 75°C, are used as criteria for assessing the quality of rye flour or meal. The water absorption of rye flour is measured on a farinograph, which makes it possible to correlate the quality index with the amount of water that must be added to the dough and determine the economically significant yield of dough and bread obtained from a given amount of flour. The absence of gluten formation in rye dough increases the role of swelling substances as a dough structure former. Water absorption of whole-ground rye flour and dough mainly depends on the content and properties of AX. The role of rye proteins in water absorption is not as significant as compared to wheat since there are more water-soluble proteins among rye proteins [11].

The swelling test is another method for assessing of the dough properties associated with the content of AX and the activity of cell wall degradation enzymes [12]. It is rarely used directly in the practice of Russian breeding since there are no demonstrating the possibility of using it to assess the baking qualities of rye flour instead of traditional assessments of amylographic viscosity.

Determining the size and structural features of AX as important determinants of bioactivity and technological functions of rye grain is still a scientific problem. The relationship between the amount of the water-soluble fraction of arabinoxylans and its viscosity properties as important dough-forming ingredients with other baking and technological properties of grain has not been fully studied.

The purpose of the research is to evaluate the manifestation of indicators that determine baking and functional and technological properties and to identify correlations between these parameters in whole-grain rye flour.

MATERIALS AND METHODS

For the study, we used rye grain collected in the field experiments of the Tatar Research Institute of Agriculture (Federal Research Center "Kazan Scientific Center of the Russian Academy of Sciences") located in the Laishevsky district of the Republic of Tatarstan (2016–2018 harvest).

The objects of study were modern Russian varieties of winter rye of our own selection (Tatarskaya 1, Estafeta Tatarstana, Radon, Ogonek, Tantana, Podarok, Zilant, Populatsiya 17) and of other breeding institutions (Parcha, Pamyati Kunakbaeva). Each variety was grown on plots with a total area of 16 m^2 (counting area 12 m^2) in four repetitions in accordance with the requirements of the State Variety Testing of Agricultural Crops.

The grinding of a grain sample weighing 300 g in order to obtain meal (whole grain with a 100% yield with a different combination of particles of different sizes) was carried out on a Perten Instruments Laboratory Mill 3100 (Sweden) with a sieve size of 0.8 mm according to GOST 13586.5-85.

A total of 18 parameters that characterize the quality of grain and its raw material value were evaluated. The falling number was determined by the standard ISO 3093 (2009) method on a Falling Number 1500 device (Hagberg-Perten, Germany).

To analyze the properties of starch gelatinization, Amylograph Brabender OHG equipment (Germany, GOST ISO 7973-2013) was used, which evaluated the initial and maximum viscosity of the suspension in amylograph units (a.u.), as well as the gelatinization temperature (initial and maximum) in degrees Celsius. Another method for evaluating dough properties related to the content of the AX fraction and the activity of cell wall degradation enzymes is characteristic of swelling of the water-meal suspension (swelling test) [13]. To construct swelling curves on an amylograph, we used a sample of 130 g of rye flour (14% moisture), which was mixed with 400 cm^3 of distilled water (temperature 32–33°C) in a measuring cylinder. The addition of water was carried out slowly with continuous stirring until a homogeneous suspension was formed, which was then placed in the amylograph cup. After that, the thermostat sensor was set to 30°C and the thermostat drive was turned off so that the registration of the swelling process (in the form of a curve) occurred at this temperature for 30 min. The following characteristics were determined from the swelling curve: initial and maximum swelling (in instrument units), swelling time in minutes, swelling rate (a.u./min).

The rheological properties of the dough were evaluated on a Farinograph Brabender according to the standard method ICC 115/1. The grinding of grain prior to this analysis was carried out on a CHOPIN CD1 mill (France), standardized by AACC 26-70.01 for its implementation. Farinographic characteristics were analyzed using a 200-g sample of whole-ground rye flour (in terms of 14% moisture content), which was mixed with distilled water in a 300-g thermostatically controlled mixing bowl of the farinograph until the final dough consistency reached 300 ± 10 farinograph units after 10 min of mixing [14]. The dynamics of the viscoelastic properties of the dough was controlled by the following criteria: water-absorption capacity (WAC) (%), test formation time (minutes), dough stability during kneading (minutes), the degree of liquefaction of the dough (farinograph units), farinograph quality number (FQN) (mm), and valorimetric score (%).

To determine the content of water-soluble pentosans (WSPC) and the viscosity of water extract (VWE) of rye meal, whole-meal flour was extracted with distilled water at a temperature of 30°C for 60 min according to the method described by Boros et al. [15]. The ratio of meal and water was 1 : 5. VWE was determined by the viscometric method using domestic equipment (VPZh-1, capillary diameter 1.52 mm).

To calculate the VWE in centistokes, the following formula was used: $V = g/9.807 * T * K$, where V is the kinematic viscosity, mm^2/s; g is the free fall acceleration at the place of measurement, m/s^2; T is the liquid outflow time, s; K is the constant of the viscometer, mm^2/s^2; according to the method [16]. WSPC was measured by a biochemical micromethod adapted for rye grain using an orcine reagent [17, 18]. The protein content was analyzed by the Kjeldahl method (AOAC 984.13).

Statistical data processing was carried out using multivariate methods of statistical analysis (principal components, cluster analysis) using the XL STAT 2018.6.54644 platform.

RESULTS AND DISCUSSION

The quality of rye flour used for baking is based on the quantity and functional properties of its constituent substances.

Whole-ground rye flour, despite the growing interest in it due to healthy eating trends, is poorly evaluated in terms of quality characteristics, although it fundamentally differs from pure flour in terms of the quantitative content of bran, lipids, protein and particle size.

Flour millers rely on their own methods for evaluating batches of winter rye to ensure that flour is of the right quality. Bakers rely on their approved methods for various baking techniques. Breeders must take into account numerous proven methods when developing a variety in order to obtain objective data that determines the raw material value in order to evaluate and select the best varieties, taking into account the various needs of both the flour milling and bakery industries. Moreover, depending on the end use of a particular variety, the breeding program should apply contrasting selection criteria and appropriate equipment.

According to the results of our previous studies [19], the studied varieties of winter rye had significant differences in technological and baking properties, while, from the totality of rheological characteristics, they significantly differed only in dough stability and quality assessment by farinograph. Continuing this work, we analyzed a set of direct and indirect parameters that characterize the quality of wholemeal flour and dough based on it to identify a system of indicators that are most suitable for breeding practice.

The results of the analysis of block diagrams (Figs. 1, 2), which demonstrate the distribution of values for each of the studied traits in a group of ten studied varieties, indicate that the interquartile range corresponding to the box size and the ratios of the extreme variants differed markedly in terms of indicators, reaching individual parameters (swelling rate, VWE, dough stability, FQN) of double values (see Fig. 2). The median values of such flour and dough parameters as the onset temperature and gelatinization time, swelling time, WAC, formation time, dough stability, and degree of liquefaction turned out to be lower than the average values, which indicates the heterogeneity of varieties according to the listed characteristics. "Outliers" (points outside the blocks) observed on the diagrams—according to the characteristics of the temperature of the beginning of gelatinization, swelling time, VWE, WAC, dough stability and FQN—indicate that individual varieties were very different from the main sample.

When analyzing the relationship between the quality characteristics of wholemeal flour and dough, 29 pairs with significant correlation coefficients were identified (Table 1). As expected, FN showed a high positive correlation with peak amylograph viscosity ($r = 0.84$) and temperature at peak viscosity ($r = 0.91$). Protein content did not correlate with amylographic characteristics. A significant and positive correlation was noted between the gelatinization time and the falling number, amylogram height, gelatinization peak temperature ($r = 0.77$; 0.78; 0.85, respectively).

A high correlation was noted between the parameters of the swelling curve, namely, the maximum swelling after holding at 30°C for 30 min, with the falling number, the maximum height of the amylogram, and the viscosity of the aqueous extract (0.85; 0.90; 0.94, respectively).

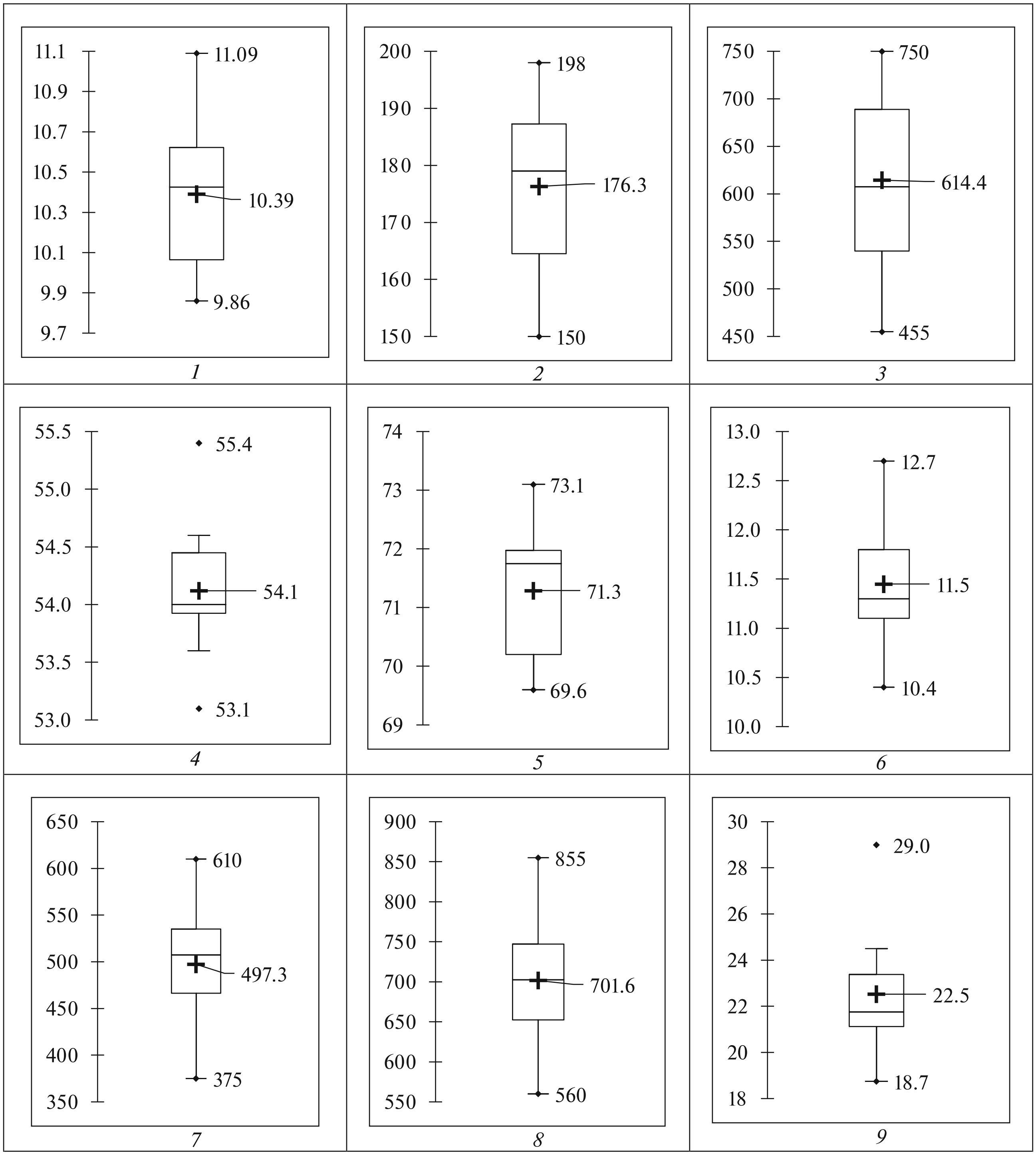

Fig. 1. Tukey's range diagram of indicators characterizing the baking qualities of wholemeal flour and the rheological qualities of the dough of winter rye varieties: (*1*) protein content in grain, %; (*2*) falling number, s; (*3*) amylogram height, a.u.; (*4*) gelatinization start temperature, °C; (*5*) gelatinization peak temperature, °C; (*6*) gelatinization time, min; (*7*) the beginning of swelling, a.u.; (*8*) maximum swelling, a.u.; (*9*) swelling time, min.

The same strong relationships (slightly different in the value of the correlation coefficient) with the same parameters were found in the VWE. The closest correlations were noted between the initial swelling and the indicators of maximum swelling, the water extract viscosity, and the content of water-soluble pentosans (see Table 1).

The water-absorption capacity of flour depends on its water-binding capacity and determines the yield of dough and the amount of water added during dough

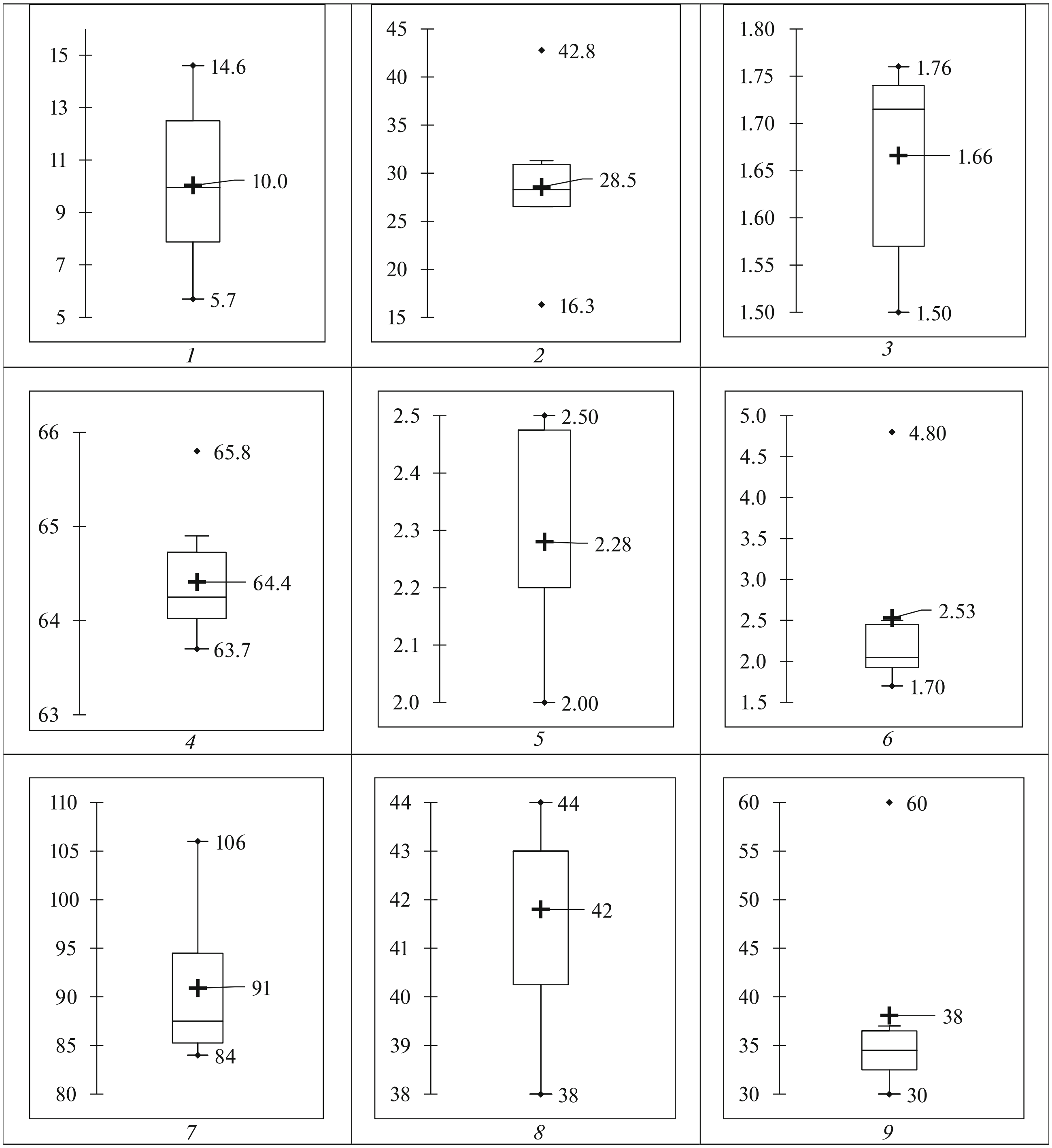

Fig. 2. Tukey's range diagram of 18 indicators characterizing the baking qualities of wholemeal flour and the rheological qualities of the dough of winter rye varieties: (*1*) swelling rate, a.u./min; (*2*) water extract viscosity, cSt; (*3*) content of water-soluble pentosans, %; (*4*) water-absorption capacity of the dough, %; (*5*) dough formation time, min; (*6*) dough stability, min; (*7*) degree of liquefaction of the dough, f.u.; (*8*) valorimetric grade, %; (*9*) farinograph quality number, mm.

preparation. Water absorption significantly positively correlated with swelling rate ($r = 0.63$), while dough formation time with VWE ($r = 0.66$). A significant negative correlation was noted between the valorimetric evaluation of the dough and the degree of its dilution ($r = –0.91$). The swelling onset index at 30°C was highly correlated with maximum swelling, VWE, and WSPC. The dough stability, which characterizes the duration of maintaining the maximum level of consistency of the kneaded dough, was in a significant nega-

Table 1. Matrix of coefficients of pair correlation of quality traits of rye grain, rye meal, and dough

Trait*	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1.00																	
2	–0.50	1.00																
3	–0.18	**0.84**	1.00															
4	–0.17	0.50	0.28	1.00														
5	–0.28	**0.91**	**0.81**	0.53	1.00													
6	–0.22	**0.77**	**0.78**	0.00	**0.85**	1.00												
7	0.00	0.55	0.55	0.13	0.42	0.42	**1.00**											
8	–0.09	**0.85**	**0.90**	0.30	**0.80**	**0.76**	**0.76**	1.00										
9	0.08	–0.24	0.03	0.12	–0.07	–0.16	–0.62	–0.30	1.00									
10	0.17	**0.68**	**0.80**	0.20	**0.83**	**0.86**	0.55	**0.85**	–0.17	1.00								
11	–0.09	**0.82**	**0.90**	0.18	**0.72**	**0.74**	**0.66**	**0.94**	–0.29	**0.77**	1.00							
12	0.25	0.29	0.25	0.49	0.24	–0.03	**0.66**	0.37	–0.44	0.28	0.34	1.00						
13	0.33	0.24	0.38	0.21	0.50	0.46	0.40	0.40	0.11	**0.63**	0.18	0.30	1.00					
14	0.38	0.32	0.38	–0.14	0.37	0.53	0.25	0.53	–0.36	0.60	**0.66**	0.10	0.07	1.00				
15	**–0.69**	0.38	0.12	0.24	0.06	–0.07	0.26	0.09	–0.40	–0.22	0.18	0.32	–0.53	–0.30	1.00			
16	0.17	–0.40	–0.05	–0.10	–0.53	–0.56	–0.17	–0.20	0.46	–0.41	–0.15	–0.13	–0.31	–0.34	–0.02	1.00		
17	–0.24	0.28	–0.19	0.12	0.33	0.31	0.08	0.06	–0.56	0.15	0.01	0.03	0.00	0.30	0.11	**–0.90**	1.00	
18	–0.60	0.35	0.14	0.19	0.03	–0.08	0.25	0.08	–0.38	–0.23	0.22	0.38	–0.55	–0.21	**0.98**	0.00	0.07	1.00

* 1—Protein content in the grain; 2—falling number; 3—amylogram height; 4—gelatinization start temperature; 5—gelatinization peak temperature; 6—gelatinization time; 7—beginning of swelling of rye meal at 30°C; 8—maximum swelling of rye meal meal at 30°C after exposure for 30 min; 9—swelling time of rye meal; 10—swelling rate of rye meal; 11—viscosity of water extract of rye meal; 12—content of water-soluble pentosans in rye meal; 13—water-absorption capacity of dough; 14—dough formation time; 15—dough stability; 16—degree of dough liquefaction; 17—valorimetric evaluation of the dough; 18—farinograph quality number. The critical value of the correlation coefficient is $r = 0.63$; significant correlation coefficients are highlighted in bold.

tive correlation with the protein content ($r = –0.69$) and a high positive correlation with the farinograph quality number ($r = 0.98$).

Thus, the structure of the "rye meal-water" complex is determined by the mutual influence of many components on which the baking qualities of rye grain and the quality of the final product, rye bread, depend.

Checking the correlation between VWE measured using a capillary viscometer with maximum swelling (final viscosity on the swelling curve) after holding at 30°C for 30 min showed that the viscosity of the water extract positively and significantly correlates with the maximum swelling of rye meal (Fig. 3). The linear regression equation is as follows: $y = 0.0828x – 29.536$. VWE can serve as an effective assessment for measuring the viscosity properties of wholemeal flour solutions and determining the relationship between functionality and structural properties. Similar approaches have been proposed by other authors [20]. Rye populations with high viscosity had better baking characteristics than populations with low viscosity.

According to Goncharenko et al. [21], they outperformed other varieties in terms of falling number (by 90 s), amylogram height (by 328 a.u.), and gelatinization temperature (by 2.5°C).

Therefore, emphasis was placed in the work on the analysis of the most differentiating indicators of the amount of arabinoxylans and their viscous properties, determined by indirect estimates through swelling, viscosity of the water extract, and water-absorption capacity.

Although there are quite a lot of research results in the domestic literature on VWE [2, 22], the swelling assessment is hardly used to characterize whole-ground flour.

On the cluster analysis dendrogram (Fig. 4), the abscissa shows the numbers assigned to a certain feature in the order of their similarity; along the y-axis are lines reflecting the distances between these objects.

Cutting the dendrite according to the chosen level of similarity (distance) leads to the selection of the most similar groups of objects. In our study, the first enlarged cluster included VWE, swelling rate, amylogram height, maximum swelling, falling number, temperature, and gelatinization time. The first two of them are characterized by significant genotypic variation and can be used as breeding criteria.

The second cluster grouped the temperature of the beginning of gelatinization, the onset of swelling, water-absorption capacity, WSPC, protein content, and dough formation time. Under mechanical load,

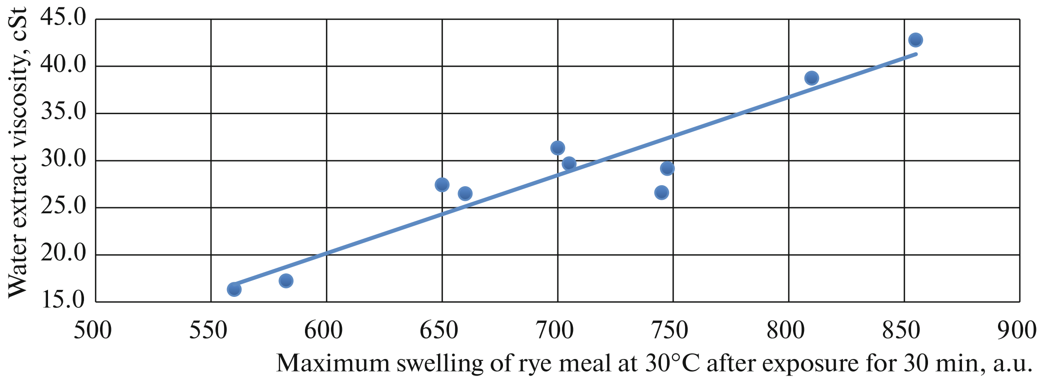

Fig. 3. Relationship between the viscosity of the water extract and the swelling test.

there is first a continuous decrease in the viscosity of the rye dough. This phenomenon is primarily facilitated by the breakdown of proteins. Of course, pentosans also play a role in these changes, but the point is most likely in the reactions between proteins and pentosans. However, the process has not been fully elucidated and, therefore, definitely requires further research.

We combined four indicators in the third cluster: dough stability, farinograph quality number, swelling time, and degree of liquefaction. These features demonstrate the water-binding and water-retaining role of AX. The long molecules of soluble pentosans form a branched network that is highly absorbent and forms sticky, gel-like solutions. The formation process and the consistency of the dough depends on quantity and the structure of this network. As a rule, in breeding studies, attention is first of all paid to the enzymatic activity of α-amylase at high temperatures, which is recorded on an amylograph and a device for measuring the falling number (signs of the first cluster).

The values of these indicators make it possible to predict the state of starch in grain or flour and its degradability. The increased action of amylases leads to the fact that a significant part of the starch is hydrolyzed during fermentation and baking, and this process is accompanied by the formation of a large amount of low molecular weight dextrins. As a result, the starch and pentosans in the dough do not bind all the water, and the presence of free moisture makes the crumb of rye bread sticky and wrinkled.

It is important to note that such feature of cluster 1 as the rate of swelling of the water-meal suspension, determined by the analysis of amylographic curves without heating at a constant temperature of 30°C for 30 min also showed significant intervarietal variation (see Fig. 2). This indicator additionally confirms the differences in the behavior and structural features of water-soluble AX, whose action, due to their branched configuration, is aimed at water binding and gelatinization of solutions. At temperatures above 30°C, hydrogen bonds break in starch molecules, leading to a change in its microstructure. At the same time, optimal conditions are formed for the action of many enzymes, including those catalyzing the hydrolysis of high-molecular and insoluble AX. Therefore, the swelling rate is an important criterion for the influence of water-soluble pentosans and should be taken into account in breeding programs.

From all of the traits grouped into the second cluster, in addition to protein content, attention should be

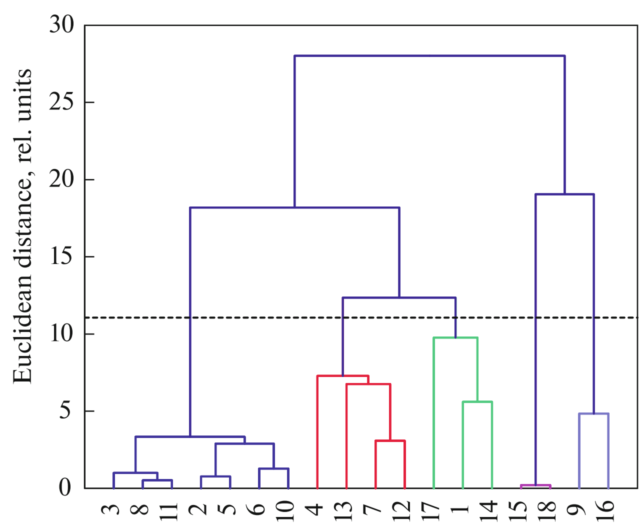

Fig. 4. Dendrogram of grain-quality traits and test varieties of winter rye. The numbers indicate the following indicators: 1—protein content in grain; 2—falling number; 3—amylogram height; 4—start gelatinization temperature; 5—peak gelatinization temperature; 6—gelatinization time; 7—beginning of swelling of rye meal at 30°C; 8—maximum swelling of rye meal at 30°C after holding for 30 min; 9—swelling time of rye meal; 10—rate of swelling of rye meal; 11—viscosity of water extract of rye meal; 12—content of water-soluble pentosans in rye meal; 13—water-absorption capacity of dough; 14—dough formation time; 15—dough stability; 16—degree of dough liquefaction; 17—valorimetric evaluation of the dough; 18—farinograph quality number.

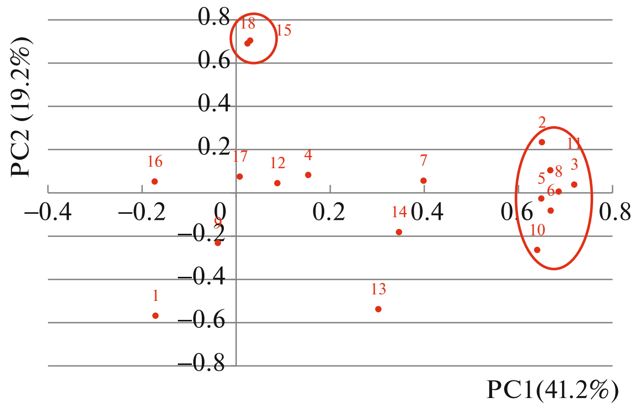

Fig. 5. Distribution of 18 qualitative features of ten varieties of rye on planes in coordinates 1 and 2 (PC1 and PC2) of the principal components calculated using the PCA method: PC1—41.2% of the explained variance; PC2—19.2% of the explained dispersion; 1–18 are the numbers of features shown in Fig. 4.

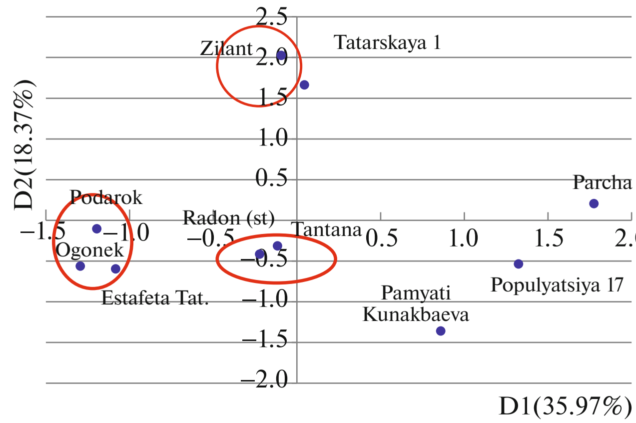

Fig. 6. Distribution of ten varieties of rye for 18 quality features on the planes in coordinates 1 and 2 (D1 and D2) of the principal components calculated by the PCA method with varimax rotation (D1—35.97% of the explained variance; D2—18.37% of the explained variance).

paid to WSPC and WAC. The change in the viscosity of the swelling and then gelatinizing starch has a significant impact on the formation of the bread crumb.

It has been theoretically proven that the baking qualities of rye flour, unlike wheat flour, can be fully preserved even with the complete removal of grain reserve proteins. This is due to the fact that water-soluble pentosans serve as the components of the dough process [23, 24].

This distinguishes rye dough from wheat dough, in which gluten proteins are responsible for the retention of gases and the properties of the crumb. High water-absorption capacity determines the behavior of the dough during technological operations and characterizes the flour-grinding qualities of winter rye grains. In finely ground rye flour, in contrast to whole-ground (coarse) flour, the water-absorption capacity will be higher due to the larger total area and small particle size that can colloidally bind water during dough kneading, while the gas-retaining capacity decreases.

In our opinion, the most important traits for selection of the third cluster indicators are the indicator of dough stability and FQN. The first parameter fixes the time during which its consistency remains unchanged, with a higher value indicating that the flour colloids take longer to fully hydrate due to the increased water-absorption capacity of the AX. This obviously increases the time required for all ingredients to be homogenized and integrated into a stable dough structure. The farinograph quality number comprehensively characterizes the rheological properties of the dough due to the different ability of the arabinoxylan fraction of rye to rapidly hydrate and retain water in a bound state. From an applied point of view, it fixes the structure, balance, and elasticity of the dough, which directly affect the efficiency of the baking technology.

Principal component analysis (PCA) was then applied to the correlation matrix. The peculiarity of this method is that it allows one to identify possible differences in the degree of importance between individual traits (Fig. 5), when differences between varieties are not considered, and, conversely, between varieties (Fig. 6) without taking into account heterogeneous traits, when all parameters are considered equally. In addition, PCA allows one to visualize the variables under study in a coordinate system for a joint analysis of interrelated characteristics. The total percentage of explained variance in our study was 60.4% (see Fig. 5).

It has been established that seven features are rather "heaped" in the first coordinate quarter. According to the given data, they are autocompensatory. At the same time, some of these features seem redundant, and they are proposed to be eliminated, leaving only three: the falling number, the swelling rate, and the viscosity of the water extract. This will lead to an improvement in the breeding process for grain quality, especially in the early stages of selection. The first determinant reveals the retrogradation of starch by amylolytic enzymes, the second determines the behavior and structural features of water-extractable AX. The third trait (VWE) serves as the resulting indicator of many properties: the amount of pentosans, their solubility, water-binding and water-retaining capacity, molecular weight, etc. Therefore, depending on the available instrumental and analytical base, a number of such combinations of traits useful for assessing the raw material suitability of varieties can be proposed: 2 + 11, 3 + 11, 2 + 10, 3 + 10, 8 + 10 (character numbers are shown in Fig. 4).

On the distribution graph of 18 qualitative traits of ten rye varieties on the planes in coordinates 1 and 2 (PC1 and PC2) of the main components (see Fig. 5), two indicators almost coincided: dough stability and farinograph quality number. Therefore, it is possible to use only one indicator, FQN, which gives generalized information about the quality of the dough, including its characteristics in terms of formation time, resistance to kneading, and degree of liquefaction. In addition, unlike other indicators recorded on the farinograph, it differentiates varieties well. The rest of the features are fairly evenly distributed in the coordinate system, so their reduction requires verification on genetically more diverse material.

An analysis of the distribution of winter rye varieties in a multidimensional space indicates that Tatarskaya 1 and Zilant varieties are closely located at the top of the coordinate plane with high WSPC, VWE, and indicators characterizing the amylolytic properties of flour. These varieties are improvers, consistently showing their high baking properties in different years. Their grain can be used to "correct" the quality of grain and/or flour with insufficient baking conditions. In the center of the biplot, there are Radon and Tantana varieties with optimal baking characteristics, which grain can be used for baking in a "pure form."

Varieties Ogonek, Podarok, and Estafeta Tatarstana with the best fodder qualities, as well as with possibility of use in distillation, are grouped into a block.

They are characterized by low VWE and WSPC rates. Separate points on the graph show the varieties Pamyati Kunakbaeva, Populatsiya 17 (a new variety of our selection), and Parcha. They probably differ from those previously named in terms of certain indicators or their combination. It should be noted that the positive and negative areas of space are largely arbitrary and have a mathematical rather than biological significance. It is important that the identified classes of varieties do not overlap and are located in different areas of the two-dimensional plane, which indicates significant differences between them.

Thus, the qualitative characteristics of wholeground rye flour are determined by a large group of properties and structural components of the grain.

The falling number and amylographic characteristics provide valuable information on the degree of gelatinization of starch under the influence of amylolytic enzymes.

The content of water-soluble pentosans characterizes the water-absorption capacity of various components of the swelling of rye flour, while structural features and solubility are the most important viscosity properties. The viscosity of the water extract based on rye meal is a key parameter for characterizing such a system. Its quantitative expression influences both the choice of test methods and determining the suitability of grain of different winter rye varieties for processing.

Evaluation of 10 winter rye varieties of Russian breeding according to 18 indicators of baking and rheological properties using different evaluation methods revealed a number of the most significant criteria for inclusion in breeding programs: falling number, aqueous extract viscosity, swelling rate, protein content, content of water-soluble pentosans, water absorption capacity, test stability and farinograph quality number.

Three clusters of grain-quality characteristics have been identified, according to which breeding work should be carried out in the future to create baking and fodder varieties of winter rye. In the early stages of breeding for the evaluation of wholemeal flour, only four characteristics are crucial: the falling number, the swelling rate, the viscosity of the water extract, and the farinograph quality number. As a result of the principal components analysis, it was also proven that there are significant differences between the studied varieties in terms of a set of characteristics that characterize their raw material value.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

COMPLIANCE WITH ETHICAL STANDARDS

The study was performed without the use of animals or people as subjects.

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