AGRICULTURAL BIOLOGY,
2017, V. 52, № 5, pp. 1041-1048
(SEL'SKOKHOZYAISTVENNAYA BIOLOGIYA)

ISSN 2412-0324 (English ed. Online)
ISSN 0131-6397 (Russian ed. Print)
ISSN 2313-4836 (Russian ed. Online)

Genetic and physiological basis of crop breeding

UDC 633.14:631.524.6

doi: 10.15389/agrobiology.2017.5.1041rus
doi: 10.15389/agrobiology.2017.5.1041eng

PENTOSAN CONTENT GENOTYPIC VARIABILITY IN WINTER RYE GRAIN

M.L. PONOMAREVA, S.N. PONOMAREV, M.SH. TAGIROV, L.F. GILMULLINA, G.S. MANNAPOVA

Tatar Research Institute of Agriculture, Federal Agency of Scientific Organizations, 48, Orenburgskii tract, Kazan, Republic of Tatarstan, 420059 Russia, e-mail smponomarev@yandex.ru (corresponding author), tatniva@mail.ru, lilya-muslima@mail.ru, mgs1980@mail.ru
ORCID:
Ponomareva M.L. orcid.org/0000-0002-1648-3938
Ponomarev S.N. orcid.org/0000-0001-8898-4435
Tagirov M.Sh. orcid.org/0000-0002-7882-7783
Gilmullina L.F. orcid.org/0000-0001-9358-5471
Mannapova G.S. orcid.org/0000-0002-9097-783X
The authors declare no conflict of interests
Received February 6, 2017

Abstract

Varieties intended for diverse use are modern priority in winter rye (*Secale cereale* L.) breeding. Composition and content of pentosans are indicators to diversify rye grain use. The aim of this work was estimation of variability in total arabinoxylans and soluble arabinoxylans in rye grain. Pentosans content was determined by high performance liquid chromatography in the HPLC-RI system (JASCO Deutschland GmbH, Germany), by chemical micro method with use of orcin-chloride, and indirectly by determining the viscosity of water extract (VWE). As a result, the samples with low and high pentosan content were identified at the linear, population and hybrid level in domestic and foreign gene pools. It was shown that Russian population varieties and high-pentosan lines selected at Tatar Research Institute of Agriculture stood out due to high rates of general pentosan level and extracted viscosity. The relationship between VWE and the content of water-soluble pentosans in the studied quantitative limits with a high probability (95 %) has a rectilinear character. In low pentosans lines originated from Tatar Research Institute of Agriculture VWE amounted to 6.40-of 6.45 centistokes (sSt), in the domestic population varieties VWE ranged from 15.40 to 34.50 sSt, and in hybrid varieties from Germany VWE reached 47.50 sSt. So we have a gene pool sufficient for baking rye breeding. In high-pentosan forms, we found the high significant positive correlation between the total content of pentosans, viscosity of water extracts and water-soluble fraction. An indirect estimate of pentosans fraction through determination of the water extract viscosity of rye meal allows to start selection in the early steps of breeding and to analyze a large number of samples in a relatively short time. Further search is necessary to select donor lines with low total level of arabinoxylans and water-soluble fraction. It is difficult to phenotypically evaluate low-pentosans plants based on an indirect indicator of viscosity only. Low pentosan lines had a significant correlation between VWE and the water-soluble fraction (r = 0.745, P = 0.05). Heritability of water extract viscosity of grain meal was rather high (H^2 = 0.71), and genotypic variation coefficient reached 32.53 %, indicating advisability of VWE improving by breeding techniques. Heritability index of water-soluble pentosan content was 0.50, and genotypic coefficient of variation was 13.02 %, so the impact of breeding on these indicators should be low. The presented genotypic variability parameters are applicable only to the genotypes used in our experiment. The smallest amounts of water-soluble pentosans in flour and meal were characteristic of the Russian varieties Marusenka, Ogonek, Chulpan 7. We revealed a low content of water-soluble fraction in the bran in variety Ogonek. To distinguish rye genotypes more precisely, it is necessary to develop effective tests which will allow to assess water absorption, viscosity and solubility of pentosans (high-molecular arabinoxylans) in addition to their quantitation in grain grind products.

Keywords: winter rye, pentosans, fractions, arabinoxylan, viscosity of water extract, meal, variety, lines, heritability, genotypic variability

Rye is superior to wheat in minerals and lysine and dietary fiber (cellulose) [1, 2]. In addition to starch, amounting 65 % of dry matter, the richest components in whole grain rye are non-starch polysaccharides (NSPs) (17 %).

These macromolecules are the main elements of cell walls. The main non-starch polysaccharides are arabinoxylans (AXs) which make about 8 % of ray grain and are synthetized from two sugars, L-arabinose and D-xylose [3-5].

The content and qualitative composition of pentosans, as well as their state (water absorption, viscosity, solubility in water), determine the diversification of rye grain use [6-8]. Good organoleptic and baking quality, freshness and dietary properties of rye bread are due to starch-arabinoxylan complexes [9-12]. At the same time, pentosans, more specifically, high-molecular arabinoxylans, are the main factor limiting using rye when for feeding animals, especially monogastric [13, 14].

The molecular structure and structural organization of arabinoxylans determine their physical properties. Long molecules of soluble pentosans can form a network, possessing high absorption capacity, and sticky gel-like solutions. The anti-nutritional properties of pentosans are due to the ability to bind water, the amount of which can be 10 times greater than their own weight. In the digestive tract of the most sensitive groups of farm animals (poultry and swine), when eating food made of rye grain, a highly viscous suspension is formed that envelops the granules of starch and proteins, which limits the absorption of already digested protein, starch, fat and other nutrients. As a result, indigestion, weakening and a decrease in productivity occur. A decrease in the amount of pentosans, primarily the water-soluble group, contributes to the improvement of forage properties of rye grain [15]. According to D. Boros et al. [16], the number of pentosans varies depending on the genotype from 35 to 88 mg/g, which allows selection of forms with a high and low content of the water-soluble fraction. As per H.-U. Jürgens et al. [17], the total number of pentosans varied from 89 to 103 mg/g, and the extractable viscosity ranged from 2.6 to 5.1 centistokes (cSt).

Many researchers suggest an indirect method of measuring amount of pentosans by viscosity of grain meal water extract (VWE) [18-20]. The viscosity of the water-protein meal suspension can serve as an integral indicator of the quality of breeding material, delimiting rye lines for bakery and fodder [22]. The heritability of this property differs in divergent selection and depends on the genotype [15, 22, 23]. In this case, the VWE value depends both on genotypic [24, 25] and environmental factors [26, 27]. The greatest differentiating ability is manifested in the years with optimum and average arid weather conditions during the filling period, which are most favorable for selection for this feature [28)]. In connection with the foregoing, it is important to identify the economic value of each variety of winter rye as a raw material.

In the present study, we identified rye genotypes, contrasting in pentosans, by high-performance liquid chromatography and extracted viscosity and obtained mapping hybrid populations to be used in marker-assisted and traditional selection.

The aim of this paper was to estimate the variability of total pentosans and the content of water-soluble fraction of arabinoxylans in Russian and foreign populations, hybrids and lines of winter rye.

Techniques. Studies of winter rye (*Secale cereale* L.) grain were carried out in 2010-2016 at the Tatar Scientific Research Institute of Agriculture (TatNIISH). Population varieties of Russian and own selection, samples from the EU collection, low pentosans and high pentosans lines, hybrids of the second generation, obtained at TatNIISH by crossing contrasting lines, and hybrid varieties of KWS Lochow GmBH (Germany) were studied. A total of 110 samples were analyzed. Plants were grown annually in competitive variety testing, in collection nursery and in hybrid nurseries. Two weeks after harvesting, the grain was ground using a Laboratory Mill 3100 (Perten Instruments, Germany), flour and meal were sampled as per State

Standard GOST 13586.5-85. Pentosans were quantified by high-performance liquid chromatography in a HPLC-RI system (JASCO Deutschland GmbH, Germany) using a RF-10AXL fluorescent detector and 465 autosampler (Kontron Instruments, Germany) [17]. The qualitative composition of pentosans was evaluated according to the total number of arabinoxylans (total arabinoxylans, TAX) and the fraction of water-soluble arabinoxylans (soluble arabinoxylans, SAX).

The extraction of the samples to determine the content of water-soluble pentosans (WSP) and the viscosity of water extract (VWE) was carried out according to the procedure described by D. Boros et al. [16]. Viscosity of water extracts was measured using a capillary viscometer VPZH-1 (Labtech, Russia) with a capillary diameter of 1.52 mm [19]. The ratio of meal and water was 1:5. The kinematic viscosity of the water extract was calculated in centistokes according to the formula $V = g/9.807 \cdot T \cdot K$, where K is the constant of the viscometer, mm^2/s^2; V is the kinematic viscosity, mm^2/s; T is the time of flow of the liquid, s; g is the acceleration of gravity at the place of measurement, m/s^2. The content of water-soluble pentosans was determined by the micro-method with orcine chloride [29], as modified for rye grain [30].

Phenotypic and genotypic variance, as well as coefficient of variation calculated based on a two-factor dispersion analysis with the Duncan multiple rank test [31]. To evaluate the genotypic variability and calculate the coefficient of heritability, the corresponding formulas [31, 32] were applied:

$$\sigma_p^2 = \sigma_g^2 + \sigma_e^2\ , \ \sigma_g^2 = \frac{M_g - M_e}{r},$$

$$PCV = \frac{\sqrt{\sigma_p^2}}{\bar{x}} \times 100\ \%,\ GCV = \frac{\sqrt{\sigma_g^2}}{\bar{x}} \times 100\ \%,\ H^2 = \frac{\sigma_g^2}{\sigma_p^2},$$

where σ_p^2 and σ_g^2 are the phenotypic and genotypic dispersion, respectively; σ_e^2 is dispersion of the residue, M_g is the mean square for the variants, M_e is the mean square for the residue, r is the number of replicates, PCV is the phenotypic coefficient of variation, %, GCV is the genotypic coefficient of variation, %, $\bar{x}$ is the mean value of the characteristic, H^2 is coefficient of heritability. The statistical processing was performed using the Excel 7.0 software package. The tables show the mean values (*X*) and mean errors (±Sx).

Results. Among the samples studied, a significant number of bakery varieties with high level of SAX and WSP, which have a beneficial effect on the formation of rye dough, stability of its form and the quality of bread as a whole, were identified (Table 1). Recombination breeding using European varieties and samples from the VIR collection, as well as hybrid varieties, will allow creating forms suitable for bakery. Domestic population varieties and high-pentosan selection

1. Viscosity of water extracts (VWE) and the pentosan fractions in winter rye (*Secale cereale* L.) grain (Tatar Agricultural Research Institute, 2010-2016)

Origin of samples	Number of samples	SAX, %	TAX, %	VWE, cSt	WSP, %
Population varieties of Russian selection	7	3.82±0.21	12.04±0.41	23.6±2.2	4.55±0.13
		3.12-4.66	10.53-13.72	15.4-34.5	4.03-4.97
Samples from the collections of the European Union	7	5.02±0.07	11.86±0.43	–	–
		4.74-5.35	10.86-13.8		
Low pentosan lines of the Tatar Agricultural Research Institute	10	3.76±0.13	11.04±0.18	9.5±1.2	3.33±0.39
		3.03-4.43	10.19-11.74	6.4-18.2	1.90-4.41
High pentosan lines of the Tatar Agricultural Research Institute	5	3.96±0.16	12.30±0.19	28.1±2.5	5.63±0.59
		3.65-4.42	11.68-12.82	23.5-34.7	4.59-7.14
F_2 hybrids of Tatar Scientific Research Institute	10	4.30±0.10	11.11±0.15	12.5±0.8	1.78±0.04
		3.70-4.90	10.60-12.07	9.9-18.5	1.63-1.97
Hybrid varieties of German selection	18	4.76±0.13	11.65±0.21	22.6±4.8	1.84±0.10
		3.93-5.48	10.60-12.85	8.0-47.5	1.48-2.41

N o t e. SAX — water-soluble arabinoxylans, TAX — totsl arabinoxylans, VWE — viscosity of water extract (cSt, centistokes), WSP — water-soluble pentosans. The mean values and the error of the mean (*X*±Sx) are above the line, the minimum and maximum values (min-max) are below the line. Dashes mean the absence of data.

lines of TatNIISH were distinguished by high indices of the total pentosan content (TAX) and extractable viscosity (VWE).

It was found that VWE of grain meal has a wider range of variability than WSP does. Thus, in several low pentosan lines of our selection, the VWE was 6.4-6.45 cSt. In F_2 hybrids, an intermediate inheritance of the characteristic was identified. Russian population varieties had a VWE in the range of 15.4-34.5 cSt, while in German hybrid varieties it reached 47.5 cSt.

2. Parameters of genotypic variability and heritability of water extract viscosity and the content of water-soluble pentosans in winter rye (*Secale cereale* L.) grain meal (Tatar Agricultural Research Institute, 2010-2016)

Trait	GCV, %	PCV, %	σ_p^2	σ_g^2	H^2
Viscosity of water extracts	32.53	38.58	67.068	94.336	0.71
Content of water-soluble pentosans	13.02	18.39	0.076	0.152	0.50

Note. PCV — phenotypic coefficient of variation, GCV — genotypic coefficient of variation, σ_p^2 — phenotypic dispersion, σ_g^2 — genotypic dispersion, H^2 — coefficient of heritability.

Variance analysis showed significant genotypic differences ($P \le 0.05$) both for VWE ($F_{fact.} = 15.76 > F_{theor.} = 2.18$) and WSP ($F_{fact.} = 7.03 > F_{theor.} = 2.42$) for the samples under study (Table 2). Using the heritability coefficient, we attempted to identify the proportion of the observed variation in the studied features, which depends on the genotypic differences, in the overall phenotypic variability. For the viscosity of the water extract of the grain meal $H^2 = 0.71$, which indicates the expediency of improving this feature using selection methods (see Table 2). It is also shown that 50 % of phenotypic variability in the amount of water-soluble pentosans is due to hereditary characteristics, that is, the effectiveness of selection for this trait will be low. It should be noted that heritability as a measure of a relative contribution of genetic and environmental differences to phenotypic variability has a number of limitations. In particular, heritability does not serve as an attribute of the feature, but depends on the composition of the genotypes of the population under study [33]. In another population with a different composition of genotypes, the heritability of the same feature may be different. The relative values of GCV and PCV give an idea of the magnitude of variability in the studied gene pool (see Table 2). The genotypic coefficient of variation for VWE was high (32.53 %), which influences the choice of the selection method. The differences observed in the genotypic and phenotypic coefficient of variation were practically equal for both indices.

By correlation analysis, a highly significant positive relationship between TAX and VWE ($r = 0.736$, $P = 0.05$), TAX and WSP ($r = 0.639$, $P = 0.05$) was established in a group of Russian population varieties. In high pentosan lines, created at the Tatar Agricultural Research Institute, $r = 0.790$ ($P = 0.01$) for the first pair of features, and $r = 0.812$ ($P = 0.01$) for the second one. The correlation coefficients for VWE and WSP were close to 1, that is, the content of water-soluble pentosans (arabinoxylans) in selecting forms for use in bakery can be estimated by VWE value of grain meal.

Low pentosan forms which may be used in breeding are the rarest. During their 10-year selection and study at TatNIISKH, it was shown that the average value of SAX in such samples was 3.76 % with a range from 3.03 to 4.43 % (see Table 1), which was significantly lower than that in the hybrids of German selection and in thhe collection forms. The differences in viscosity were even more pronounced. It should be noted that for now we can not specify the limiting parameters for the studied indicators for feed and bakery varieties. The smallest amount of pentosans was in flour and meal of the Marusenka, Ogonyok, Chulpan 7 grain, and a low amount of soluble arabinoxylans was detected also in bran of Ogonyok variety (Fig. 1). In all the studied varieties, the content of pentosans was the greatest in bran. This can be explained by the fact that the hull of rye grain and the aleurone layer contain up to 50 % of pentosans, while the germ and the starchy part of the endosperm, from which the flour is produced, contain no more than 15 %. The varieties Pamyati Kunakbayeva and Roksana had a higher content of pentosans in all grinding products.

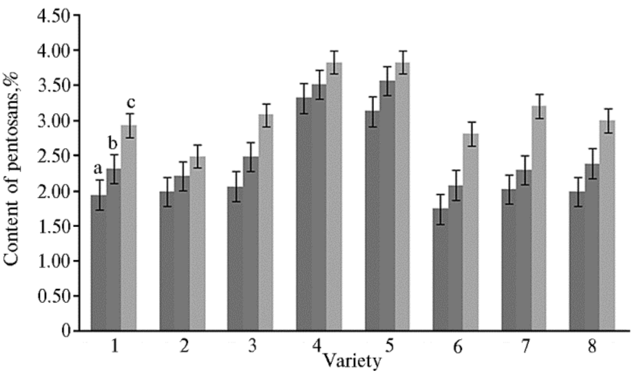

Fig. 1. The content of pentosans in flour (a)**, meal** (b) **and bran** (c) **in rye (*Secale cereale* L.) population varieties:** 1 — Tatarskaya 1, 2 — Ogonyok, 3 — Tantana, 4 — Pamyati Kunakbayeva, 5 — Roksana, 6 — Marusenka, 7 — Tatyana, 8 — Chulpan 7 (Tatar Scientific Research Institute of Agriculture, 2013-2014).

Wide screening of the breeding material involves the use of a low-cost, but objective methodology that makes it possible to quickly differentiate the created varieties for their further use. An indirect evaluation of the pentosan fraction through by viscosity of the water extracts of rye meal provides early selection and analysis of a significant number of samples during relatively short time.

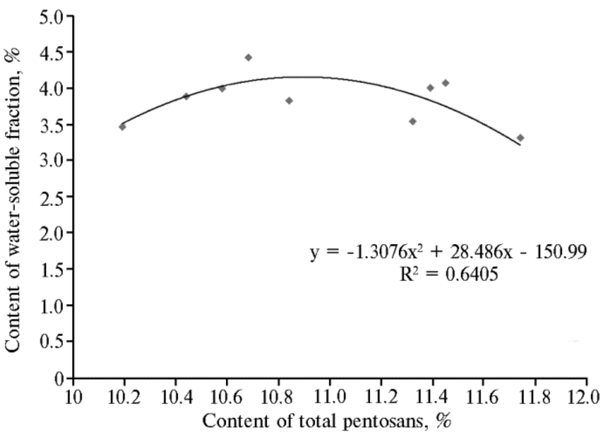

Fig. 2. Interrelation of the content of total pentosans and their water-soluble fraction in grain meal in low pentosan winter rye (*Secale cereale* L.) (Tatar Scientific Research Institute of Agriculture, 2013-2014).

The relationship between VWE and the content of water-soluble pentosans in the studied quantitative limits with high probability (95 %) was of a straightforward nature and was described by the following regression equation: $y = 0.0335x + 1.5401$, where y is the content of pentosans in the grain, %, x is viscosity of the grain meal extract, cSt.

In low pentosan lines, a significant correlation between VWE and WSP was found ($r = 0.754$, $P = 0.05$). Regression analysis showed a non-linear relationship between the amount of total arabinoxylans and their water-soluble fraction (Fig. 2). The F_2 hybrids we obtained between the contrast genotypes from Russian and foreign gene pools are of great interest. They had comparatively low VWE and WSP. Consequently, a small number of sources of low content of pentosans have been identified, the phenotypic assessment of which by VWE indirect index is difficult.

Thus, our studies have shown a sufficient gene pool for selection of bakery rye. The Russian varieties Marusenka, Ogonek, Chulpan 7 with the least amount of water-soluble pentosans in flour and meal were distinguished. A highly significant positive relationship is established between the total content of pentosans, the viscosity of the water extract and the fraction of water-soluble arabinoxylans. It is shown that the grain meal VWE value may serve as an indicator of the content of water-soluble pentosans (arabinoxylans). The phenotypic evaluation of the low-pentosan forms, based on the indirect VWE index only, is difficult. The inheritance of the viscosity of the grain meal water extract in our experiments was H^2 = 0.71, the genotypic coefficient of variation was 32.53 %. According to the content of water-soluble pentosans, H^2 = 0.50, the genotypic coefficient of variation was 3.02 %; therefore, the selection efficiency for this property will be low. The presented indexes of genotypic variability are applicable only in respect to the genotypes used in our experiment. In addition to the quantitative evaluation of pentosans (high molecular arabinoxylans) in the products of grain grinding, low cost methods to analyze their propertied (water absorption, viscosity and solubility) are required, which will make it possible to differentiate the samples more clearly.

REFERENCES

1. Nilsson M., Aman P., Harkonen H., Hallmans G., Bach K.E. Nutrient and lignin content, dough properties and baking performance of rye samples used in Scandinavia. *Acta Agric. Scand., Select. B, Soil and Plant Sci.*, 1997, 47: 26-34 (doi: 10.1080/09064719709362435).
2. Andersson R., Fransson G., Tietjen M., Aman P. Content and molecular-weight distribution of dietary fiber components in whole-grain rye flour and bread. *J. Agric. Food Chem.*, 2009, 57(5): 2004-2008 (doi: 10.1021/jf801280f).
3. Bach Knudsen K.E., Lærke H.N. Rye arabinoxylans: Molecular structure, physicochemical properties and physiological effects in the gastrointestinal tract. *Cereal Chem.*, 2010, 87(4): 353-362 (doi: 10.1094/CCHEM-87-4-0353).
4. Izydorczyk M.S., Biliaderis C.G. Cereal arabinoxylans advances in structure and physicochemical properties. *Carbohyd. Polym.*, 1995, 28: 33-48 (doi: 10.1016/0144-8617(95)00077-1).
5. Vinkx C.J.A., Delcou J.A. Rye (*Secale cereale* L.) arabinoxylans: A critical review. *Journal of Cereal Science*, 1996, 24(1): 1-14 (doi: 10.1006/jcrs.1996.0032).
6. Cui S.W., Wang Q. Cell wall polysaccharides in cereals: Chemical structures and functional properties. *Struct. Chem.*, 2009, 20(2): 291-297.
7. Bengtsson S., Andersson R., Westerlund E., Aman P. Content, structure and viscosity of soluble arabinoxylans in rye grain from several countries. *J. Sci. Food Agr.*, 1992, 58(3): 331-337 (doi: 10.1002/jsfa.2740580307).
8. Wang M.W., Vliet T.V., Hamer R.J. How gluten properties are affected by pentosans. *J. Cereal Sci.*, 2004, 39: 395-402 (doi: 10.1016/j.jcs.2004.02.002).
9. Jankiewicz M., Michniewic J. The effect of soluble pentosans isolated from rye grain on staling of bread. *Food Chem.*, 1987, 25: 241-249 (doi: 10.1016/0308-8146(87)90010-0).
10. Bonnand-Ducasse M., Della Valle G., Lefebvre J., Saulnier L. Effect of wheat dietary fibers on bread dough development and rheological properties. *J. Cereal Sci.*, 2010, 52(2): 200-206 (doi: 10.1016/j.jcs.2010.05.006).
11. Buksa K., Nowotna A., Praznik W., Gambuś H., Ziobro R., Krawontka J. The role of pentosans and starch in baking of wholemeal rye bread. *Food Res. Int.*, 2010, 43: 2045-2051 (doi: 10.1016/j.foodres.2010.06.005).
12. Hartmann G., Michael P., Peter K. Isolation and chemical characterization of water-extractable arabinoxylan from wheat and rye during bread making. *Eur. Food Res. Technol.*, 2005, 221: 487-492 (doi: 10.1007/s00217-005-1154-z).
13. Ragaee S.M., Campbell G.J., Scoles G. J., McLeod J.G., Tyler R.T. Studies on rye (*Secale cereale* L.) lines exhibiting a range of extract viscosities. 2. Rheological and baking characteristics of rye and rye/wheat blends and feeding value for chicks of wholemeals and breads. *J. Agr. Food Chem.*, 2001, 49: 2446-2453 (doi: 10.1021/jf0012289).
14. Antoniou T., Marquardt R.R., Cansfield P.E. Isolation, partial characterization, and antinutritional activity of a factor (rentosans) in rye grain. *J. Agr. Food Chem.*, 1981, 29: 1240-1247 (doi: 10.1021/jf00108a035).
15. McLeod J.G., Gan Y., Scoles G.J. Extract viscosity and feeding quality of rye. *Vortr. Pflanzenzucht*, 1996, 35: 97-108.
16. Boros D., Marquardt R.R., Slominski B.A., Guenter W. Extract viscosity as an indirect assay for water-soluble pentosans content in rye. *Cereal Chem.*, 1993, 70: 575-580.
17. Jürgens H.-U., Jansen G., Wegener C.B. Characterisation of several rye cultivars with respect to arabinoxylans and extract viscosity. *J. Agr. Sci.*, 2012, 4(5): 1-12 (doi: 10.5539/jas.v4n5p1).
18. Goncharenko A.A., Timoshchenko A.S., Berkutova N.S. Viscosity of grain water extract in winter rye as universal parameter during breeding on principal use. *Sel'skokhozyaistvennaya biologiya* [*Agricultural Biology*], 2007, 3: 44-49 (in Russ.).
19. Goncharenko A.A., Ismagilov R.R., Berkutova N.S., Vanyushina T.N., Ayupov D.S. *Doklady Rossiiskoi akademii sel'skokhozyaistvennykh nauk*, 2005, 1: 6-9 (in Russ.).
20. Cyran M.R., Ceglinska A. Genetic variation in the extract viscosity of rye (*Secale cereale* L.) bread made from endosperm and wholemeal flour: Impact of high-molecular-weight arabi-

noxylan, starch and protein. *J. Sci. Food Agr.*, 2011, 91(3): 469-479 (doi: 10.1002/jsfa.4208).
21. Gil'mullina L.F., Ponomarev S.N., Ponomareva M.L. *Materialy Vserossiiskoi nauchno-prakticheskoi konferentsii «Ozimaya rozh': selektsiya, semenovodstvo, tekhnologiya i pererabotka»* [Proc. Conf. «Winter rye: breeding, seed production, agrotechnology, and processing]. Ekaterinburg, 2012: 54-59 (in Russ.).
22. Goncharenko A.A., Ermakov S.A., Makarov A.V., Semenova T.V., Tochilin V.N., Tsygankova N.V. *Zernovoe khozyaistvo Rossii*, 2011, 5: 11-19 (in Russ.).
23. Gan Y.T., McLeod J.G., Scoles G.L., Campbell G.L. Extract viscosity of winter rye: variation with temperature and precipitation. *Canadian Journal of Plant Science*, 1997, 77(4): 555-560 (doi: 10.4141/P96-129).
24. Finnie S.M., Bettge A.D., Morris C.F. Influence of cultivar and environment on water-soluble and water insoluble arabinoxylans in soft wheat. *Cereal Chem.*, 2006, 83(6): 617-623 (doi: 10.1094/CC-83-0617).
25. Li S., Morris C.F., Bettge A.D. Genotype and environment variation for arabinoxylans in hard winter and spring wheat of the U.S. Pacific Northwest. *Cereal Chem.*, 2009, 86: 88-95 (doi: 10.1094/CCHEM-86-1-0088).
26. Hansen H.B., Rasmussen C.V., Bach Knudsen K.E., Hansen A. Effects of genotype and harvest year on content and composition of dietary fibre in rye (*Secale cereale* L.) grain. *J. Sci. Food Agr.*, 2003, 83(1): 76-85 (doi: 10.1002/jsfa.1284).
27. Martinant J.P., Billot A., Bouguennec A., Charmet G., Saulnier L., Branlard G. Genetic and environmental variations in water-extractable arabinoxylans content and flour extract viscosity. *J. Cereal Sci.*, 1999, 30(1): 45-48 (doi: 10.1006/jcrs.1998.0259).
28. Ponomareva M.L., Ponomarev S.N., Gil'mullina L.F., Mannapova G.S. *Dostizheniya nauki i tekhniki APK*, 2015, 29 (11): 32-35 (in Russ.).
29. Hashimoto S., Shogren M.D., Pomeranz Y. Cereal pentosans: their estimation and significance. I. Pentosans in wheat and milled wheat products. *Cereal Chem.*, 1987, 64(1): 30-34.
30. Delcour J.A., Vanhamel S., De Geest C. Physico-chemical and functional properties of rye nonstarch polysaccharides. I. Colorimetric analysis of pentosans and their relative monosaccharide compositions in fractionated (milled) rye products. *Cereal Chem.*, 1989, 66(2): 107-111.
31. Gomez K.A., Gomez A.A. *Statistical procedures for agricultural research.* J. Wiley and Sons, NY, 1984: 207-215.
32. Burton G.W., DeVane E.H. Estimating of heritability in tall Fescue (*Festuca arundinacea*) from replicated clonal material. *Agronomy Journal*, 1953, 45: 478-481 (doi: 10.2134/agronj1953.00021962004500100005x).
33. Rokitskii P.F. *Vvedenie v statisticheskuyu genetiku* [Introduction to statistical genetics]. Minsk, 1978: 226-278 (in Russ.).