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CROP PRODUCTION

# Dynamics of Technological and Baking Qualities of Winter Rye Grain Depending on Flour Yield and Water Extract Viscosity

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**Abstract**—Dynamics of technological and baking qualities of winter rye grain were studied depending on flour yield and water extract viscosity (WEV). Initial material consisted in six populations of winter rye obtained after ten cycles of divergent selection for WEV, which was carried out on the basis of cultivars Al'fa and Moskovskaya 12. For each cultivar, three populations contrastingly differing for WEV were identified: low viscosity ones (LV) obtained in minus selection, mean viscosity ones (MV) obtained on the basis of the original populations without selection, and high viscosity (HV) ones obtained in plus selection. For each population, three grades of flour were obtained: wholemeal flour (100% yield), medium flour (87% yield), and pure flour (63% yield). Comparative testing was carried out in 2015 and 2016: in a field experiment on 8-m$^2$ plots in three repetitions. The following traits were studied: weight of 1000 grains, nature of grain, glassiness, protein and starch contents, flour whiteness, falling number, amylogram height, starch gelatinization temperature, H/D ratio, bread volume, and crumb porosity. A prominent feature of LV-populations is the trend towards small grains, low grain nature, and lowered starch contents. For most traits, HV-populations were at the level of MV-populations. It was concluded that, during production of pure rye flour, almost all pentosans together with bran are removed from external layers of caryopsis. As a result, the share of pentosans within endosperm essentially increases. These pentosans belong to the water-soluble fraction, which is proven to be true by a sharp increase in WEV in pure rye flour in comparison with wholemeal flour. An increase in WEV in the grades of thin grinding flour occurs due to water-soluble pentosans, which are contained in bran, in deep layers of endosperm. As compared to rough grinding flour (wholemeal flour), thin grinding flour (pure flour) differed by higher whiteness (by 46.6 units), better amylogram (by 46 a. units), higher H/D ratio (by 0.04), volumetric yield (by 38 cm$^3$), and porosity of crumb of a square loaf (by 9.9%). WEV also had significant influence, which, at high expression, positively affected flour whiteness, falling number, amylogram height, starch gelatinization temperature, and shape stability of toppling bread.

*Keywords:* winter rye, cultivar, population, divergent selection, flour yield, water extract viscosity, grain baking qualities

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## INTRODUCTION

In the history of agriculture, winter rye was cultivated mainly as a grain crop. A distinctive feature of its grain is the relatively high content of nonstarch polysaccharides (pentosans), which are very important in baking but undesirable when using rye for animal fodder [1]. Pentosans are the basic substances that bind water during dough mixing; they increase its viscosity and improve physical properties [2]. Their total content in rye grain varies from 7.0 to 13.0% [3]. With respect to water, pentosans are divided into water-soluble and water-insoluble: water-insoluble pentosans (WIPs) are contained mainly in the cell membranes, and water-soluble pentosans (WSPs) are found inside their contents, but their more precise location and ratio are not yet determined. Some researchers [4] consider that rye grain with a high content of total pentosans is more suitable for baking, since these are important components of swelling in dough formation with reduced enzymatic activity. A special role belongs to WSPs, whose share in the structure of total pentosans is 20–38% [5]. Their valuable property is the ability to provide highly viscous aqueous solutions at a relatively low concentration, which is necessary in the technology of making rye dough [6].

The noted features of rye make it possible to explain why almost all of its cultivars are classified as baking and little meet the requirements for fodder grain. The reason is that the purposes of selecting rye for baking and grain-felling fitness do not overlap; therefore, they should be solved by different breeding programs [7]. Grain-felling rye, in contrast to baking rye, must contain a large amount of protein but a relatively low amount of pentose, especially their water-soluble fraction [8]. Previously, breeding of rye in this direction was not carried out, that is why the problem of pentosans began to attract the attention of many breeders. It was established [9] that the water extract viscosity (WEV) potential of a grain meal is directly related to the WSP content in the rye grain ($r = 0.97$). This served as the basis for using it as an indirect indicator of their quantitative content. It was found that pentosans are heterogeneous in molecular weight, and, therefore, can have different WEV at equal concentrations [10]. Comparison of two groups of pentosans differing by molecular weight showed [11] that polymers with a high density of substitution of xylose residues have a higher correlation with WEV than pentosans with a lower density of such substitution. This indicates a great informational value of the WEV trait in relation to the biochemical structure of pentosans. In the selection aspect, it is important that the WEV level of grain meal can serve as a good indicator of the suitability of winter rye grain for baking or fodder purposes.

The Moscow-based NIISKh Nemchinovka has been breeding winter rye for the WEV trait since 2001. A methodology for estimating the breeding material for WEV on the basis of a rotary viscosimeter was developed and tenfold divergent (multidirectional) selection for WEV on the basis of Al'fa and Moskovskaya 12 rye cultivars was carried out [12]. As a result, unique rye populations with a high contrast for WEV were obtained. This index was higher in high-viscosity (HV) populations compared to the initial form, which has a medium viscosity (MV), by 3.3–6.0 times, while it was 2.6–3.5 times lower in low-viscosity (LV) populations. A preliminary study of these populations showed that HV populations are characterized by a significantly higher yield and better grain quality than LV ones. A particularly high correlation effect was achieved for the grain nature, the falling number, the amylogram height, the shape stability of the bread, and the quality of the bread crumb. It is concluded that breeding for high WEV makes it possible to significantly improve the baking quality of grain in rye.

Selection of divergent populations revealed the need for their more in-depth study. Since HV-populations contain lots of WSPs and LV ones contain little, it is practically important to know how, against the background of changes in the WEV potential, the physicobiochemical and technological attributes of quality will change during the production of various types of flour, for example, wholemeal (100% yield), entire (95%), medium (87%), and pure rye flour (63%). It is known [13] that starch is found in the endosperm of the rye caryopsis, while other components are contained in their respective amounts in the endosperm and membranes. Therefore, whole meal flour contains relatively much fiber and is richer in proteins, vitamins, and minerals than medium and pure rye flour, which contains lots of starch in endosperm. The high content of WSPs makes rye flour very hygroscopic and prevents its sieving. With a decrease in the percentage flour yield (increase in its grade), its content of hulls reduces and the content of many other biochemical components (starch, protein, pentosans, cellulose, and fat) changes. The only component of flour whose content increases is starch. Removal of a large number of hulls during grinding favorably affects the height of the flour amylogram, improves the appearance of the baked bread (crumb and crust lighten), and increases the bread volume, porosity, and crumb elasticity [14]. The issue of changing the expression of quality attributes in flour of different viscosity and grade is not fully understood in the scientific literature, therefore its consideration is of great scientific and practical interest. The purpose of this work was to study the dynamics of the main physicotechnological and baking quality attributes of winter rye grain depending on the yield of flour during grinding and the WEV level.

## METHODS

The starting material consisted in six rye populations obtained as a result of tenfold divergent selection for WEV carried out on the basis of Al'fa and Moskovskaya 12 cultivars. The technology of divergent selection was described earlier [15]. The relative WEV of different cultivars of flour (whole meal, medium, and pure rye flour) was measured in centipoises (cP) on the rotor viscometer VT5L/R (Germany) according to the method we developed [16]. Divergent populations were obtained by mixing the reserve seeds from each of the 20 plants, which deviated by $\pm 1.5\ \sigma$ from the population mean in terms of viscosity. The thus obtained four populations (two from plus selection and two from minus selection) were annually sown on spatially isolated plots for free pollination and subsequent breeding cycles. For each cultivar, three subpopulations were compared, contrasting in terms of WEV: low-viscosity (LV) ones obtained by minus selection, medium-viscosity (MV) ones based on the initial populations without breeding, and high-viscosity (HV) ones obtained by plus selection. Comparative trials of these populations were carried out in 2015 and 2016 in the field experiment at 8-$m^2$ plots in three repetitions. After harvesting, an average sample of 3 kg grain was taken from each plot to evaluate the physical-technological and flour-baking characteristics.

Wholemeal flour with 100% yield was obtained by a single grinding of the grain using a Kamas Slago 120 mill. Medium rye flour with 87% yield and pure rye flour with 63% yield was obtained by grinding the grain in

**Table 1.** Physicobiochemical indicators of grain quality in rye populations with various WEV (average for 2015–2016)

| Trait | Al'fa | | | Moskovskaya 12 | | |
|---|---|---|---|---|---|---|
| | LV | MV | HV | LV | MV | HV |
| Viscosity of extract, cP | 1.5 | 5.0 | 11.5 | 3.0 | 6.2 | 13.7 |
| Weight of 1000 grains, g | 26.8 | 29.5 | 30.5 | 32.0 | 34.5 | 33.1 |
| Nature of grain, g/L | 689 | 729 | 720 | 696 | 730 | 720 |
| Glassiness, % | 30.5 | 43.0 | 22.0 | 28.0 | 34.0 | 13.0 |
| Protein content, % | 14.6 | 13.1 | 13.3 | 15.1 | 13.2 | 14.0 |
| Starch content, % | 51.1 | 54.7 | 53.6 | 51.6 | 54.1 | 53.0 |

the Quadratym Senior mill with an appropriate sieve position. The whiteness of the flour was determined using the SKIB-M instrument and the glassiness by cutting the grains, the amylogram height and the starch gelatinization temperature with the Brabender amylograph, the falling number (FN) using the Hagberg-Pertin instrument, and the protein and starch contents with the Spectra Star 2400 infrared spectrophotometer. Evaluation of baking qualities was carried out by the method of trial laboratory baking of straight toppling bread and panned loaf from 250 g flour. The form-stability of bread was measured as the ratio of the height of toppling bread (H) to its diameter (D), and the quality of the panned loaf was determined by measuring the volume yield of bread and the visual assessment of the physical properties of the crumb (color, stickiness, and elasticity). The porosity of the crumb of the panned loaf was determined in percent using the KP-101 standard device.

## RESULTS AND DISCUSSION

Dynamics of physicobiochemical traits of grain quality in rye populations with different WEV levels is presented in Table 1. As can be seen, multiple selection for WEV is correlated with many nonselectable quality traits. A characteristic feature of LV populations from both the cultivars is a clear trend towards fine grain, low grain nature, and reduced starch content. Relatively small grain in these populations indicates an underdeveloped endosperm, which can be detected by the low content of starch and increased protein content. For the majority of these attributes, HV populations were closer to the level of initial MV populations.

Glassiness is an important attribute of grain quality, since it reflects the structural features of the internal tissues of the caryopsis. Its magnitude is strongly influenced by many factors, especially protein content in the grain. In our experiment, LV populations were the most high-protein, but MV populations had the highest glassiness in comparison with which the glassiness of grain was lower by 6.0–12.5% in LV populations and by 21.0% in HV populations. This can be explained by significant changes in the structure of the internal tissues of the caryopsis under the influence of selection. They consist in replacing the transparent consistency of endosperm for an opaque (mealy) one. The mealy endosperm is characterized by weaker binding of starch grains to protein, which could cause a decrease in its glassiness [13]. It is important to note that high glassiness of the grain was not combined with either low or high WEV. However, since HV populations had the lowest glassiness, this makes it possible to conclude that flour from the mealy endosperm contains more WSP than flour from the glassy endosperm. The dynamics of the grain quality indicators in different rye populations for WEV in terms of the percentage flour yield is presented in Table 2.

Varietal differences between the cultivars Al'fa and Moskovskaya 12 did not significantly affect the character of the dynamics of traits with the increasing flour grade, that is, the varietal specificity was not observed for any of the studied traits. This served as the basis for averaging the data for two cultivars in order to more accurately identify differences in the dynamics of quality attributes depending on the flour grade and the level of viscosity. The dynamics of the studied quality traits based on the averaged data is graphically shown in Fig. 1.

*Water extract viscosity (WEV)*. The value of this trait was increasing significantly as the percentage yield of flour was decreasing (Fig. 1a). The average viscosity of wholemeal flour was 6.7 cP, medium flour 8.6 cP, and pure flour 10.6 cP. The peculiarity of the dynamics was that the viscosity of pure flour from the grain of LV populations, in comparison with the viscosity of wholemeal flour, increased less significantly (by 26.7–33.3%, depending on the grade) than the viscosity of pure flour from HV populations, which increased by 54.8–68.6%, which is two times higher. MV populations, irrespective of the flour grade, stably occupied an intermediate position between LV and HV populations. We explain this phenomenon by the fact that the ratio of main components of flour varies with its different yields. The increasing removal of particles from the outer layers of the endosperm together with bran, which is noted with a decrease in the percentage of flour yield, leads to a reduction in the amount of all components associated with the outer

**Table 2.** Indicators of grain quality in rye populations depending on the cultivar, viscosity level, and percentage yield of flour (average for 2015–2016)

| Grade and yield of flour, % | Al'fa | | | Moskovskaya 12 | | |
|---|---|---|---|---|---|---|
| | LV | MV | HV | LV | MV | HV |
| Water extract viscosity, cP | | | | | | |
| Wholemeal (100%) | 1.5 | 5.0 | 11.5 | 3.0 | 5.2 | 13.7 |
| Medium (87%) | 1.7 | 7.6 | 13.1 | 3.5 | 7.8 | 17.6 |
| Pure (63%) | 1.9 | 8.2 | 17.8 | 4.0 | 8.7 | 23.1 |
| Whiteness of flour, % | | | | | | |
| Wholemeal (100%) | 0 | 2.0 | 4.2 | 0 | 3.3 | 3.6 |
| Medium (87%) | 24.6 | 45.1 | 39.1 | 33.6 | 41.8 | 38.1 |
| Pure (63%) | 36.6 | 52.4 | 54.4 | 46.6 | 55.1 | 47.8 |
| Falling number, s | | | | | | |
| Wholemeal (100%) | 138 | 283 | 235 | 129 | 215 | 202 |
| Medium (87%) | 166 | 279 | 243 | 140 | 215 | 202 |
| Pure (63%) | 161 | 263 | 253 | 144 | 226 | 188 |
| Height of amylogram, a. unit | | | | | | |
| Wholemeal (100%) | 177 | 337 | 355 | 195 | 267 | 350 |
| Medium (87%) | 210 | 390 | 462 | 208 | 360 | 435 |
| Pure (63%) | 187 | 367 | 475 | 220 | 320 | 385 |
| Gelatinization temperature, °C | | | | | | |
| Wholemeal (100%) | 63.8 | 69.2 | 66.3 | 61.0 | 63.7 | 62.5 |
| Medium (87%) | 63.7 | 68.5 | 64.8 | 59.8 | 62.6 | 60.9 |
| Pure (63%) | 63.7 | 67.4 | 65.8 | 59.5 | 63.8 | 61.0 |
| Toppling bread: H/D ratio | | | | | | |
| Wholemeal (100%) | 0.11 | 0.29 | 0.39 | 0.29 | 0.33 | 0.39 |
| Medium (87%) | 0.10 | 0.32 | 0.40 | 0.29 | 0.35 | 0.43 |
| Pure (63%) | 0.09 | 0.31 | 0.44 | 0.28 | 0.40 | 0.48 |
| Panned loaf: volume, $cm^3$ | | | | | | |
| Wholemeal (100%) | 313 | 300 | 273 | 304 | 320 | 313 |
| Medium (87%) | 363 | 337 | 323 | 317 | 340 | 317 |
| Pure (63%) | 367 | 344 | 320 | 365 | 330 | 320 |
| Porosity of crumb, % | | | | | | |
| Wholemeal (100%) | 54.8 | 52.1 | 50.1 | 54.2 | 60.1 | 58.4 |
| Medium (87%) | 62.5 | 64.0 | 60.4 | 62.0 | 62.4 | 62.6 |
| Pure (63%) | 65.5 | 63.4 | 62.5 | 67.7 | 63.9 | 65.5 |

layers of grain (protein, fat, fiber, and minerals). It is known that the subaleuronic layer in rye is rich in pentosans, and the average level of their content in the whole grain is much higher than in the endosperm. According to R.J. Henry [3], the content of pentosans in the whole grain of rye in terms of dry matter is 9.0% and that in the endosperm is 3.9%. Proceeding from this, it can be assumed that, in the production of pure flour, almost all peripheral pentosans are removed together with bran, because of which the share of the remaining endospermal pentosans significantly increases. The fact is that their greatest part falls for the water-soluble fraction, which is confirmed by the sharply increased level of viscosity in this flour grade. Consequently, the increase in WEV as the grade of rye flour increases is due to the increase in the proportion of WEV contained not in the bran but in the deep layers of the endosperm, where they, due to their high water-absorbing capacity, envelop the starch grains and protect them from the action of amylolytic enzymes [13].

*Whiteness of flour.* This trait directly affects the color of the bread crumb. Its value depends on the color of the grain and the degree of removal of its peripheral parts during flour production. The whiteness of flour essentially depended on its percentage yield. Wholemeal flour with 100% yield, as expected, had low whiteness of flour, 2.2 units on average for the cultivars (Fig. 1b). Medium flour (87% yield) differed from the wholemeal one by the lower content of hulls and the aleurone layer of the grain as well as a higher degree of grinding. As a result, the whiteness of flour multiplied many times and amounted to an average of 37.1 units. Pure flour (63% yield), due to a special grinding technology, contains lots of starch and little protein and fiber and consists of finely ground endosperm with a small admixture of particles of the aleuron layer and the fruit shells. For this reason, its whiteness is much higher than that of medium flour and reaches an almost limit level of 48.8 units. Low WEV negatively affects the whiteness of flour, while high WEV affects it positively, which can be visually observed against the background of medium and pure flour. The whiteness of flour in LV populations was the lowest (23.6 units), while it increased significantly and amounted to 33.3 and 31.2 units, respectively, in MV and HV populations. We explain this by the dominant influence of starch. LV populations are not distinguished by high whiteness, because, compared to MV and HV populations, they have relatively small grains with low nature, which results in a low content of starch. In addition, the grain envelope in LV populations is thinner, it is ground into a fine powder, which passes through the sieves and remains in the flour, giving it a greyish shade. MV and HV populations are characterized by a larger grain with high nature. It contains more starch, which gives the flour white color with a bluish tint and increases the degree of whiteness of flour as its yield decreases.

*Falling number (FN)*. The magnitude of this trait did not change significantly with the decrease in the percentage of flour yield (Fig. 1c). This indirectly confirms that the activity and content of enzymes that break down the starch do not change during grinding. The average value of FN in LV, MV and HV populations of the Al'fa cultivar was 220 s for wholemeal flour, 229 s for medium flour, and 226 s for pure flour; for similar populations of the Moskovskaya 12 cultivar, it was 182, 187, and 186 s, respectively. It follows from this that differences in the grinding technology did not significantly affect the activity and quantity of amylolytic enzymes of grain; that is, it is not possible to improve the falling number by increasing the flour grade, which is not noted in relation to WEV. The lowest falling numbers were characteristic of relatively high-protein (low-starch) LV populations (147 s), while the highest ones were characteristic of low-protein (high-starch) MV populations (247 s). Cultivars of flour from the grain of HV populations also had a high FN (221 s), but they were inferior to the MV populations by 26 s, which can be explained by their lower (by 1.1%) content of starch (Table 1). These data show that, at the level of MV and HV populations, there is

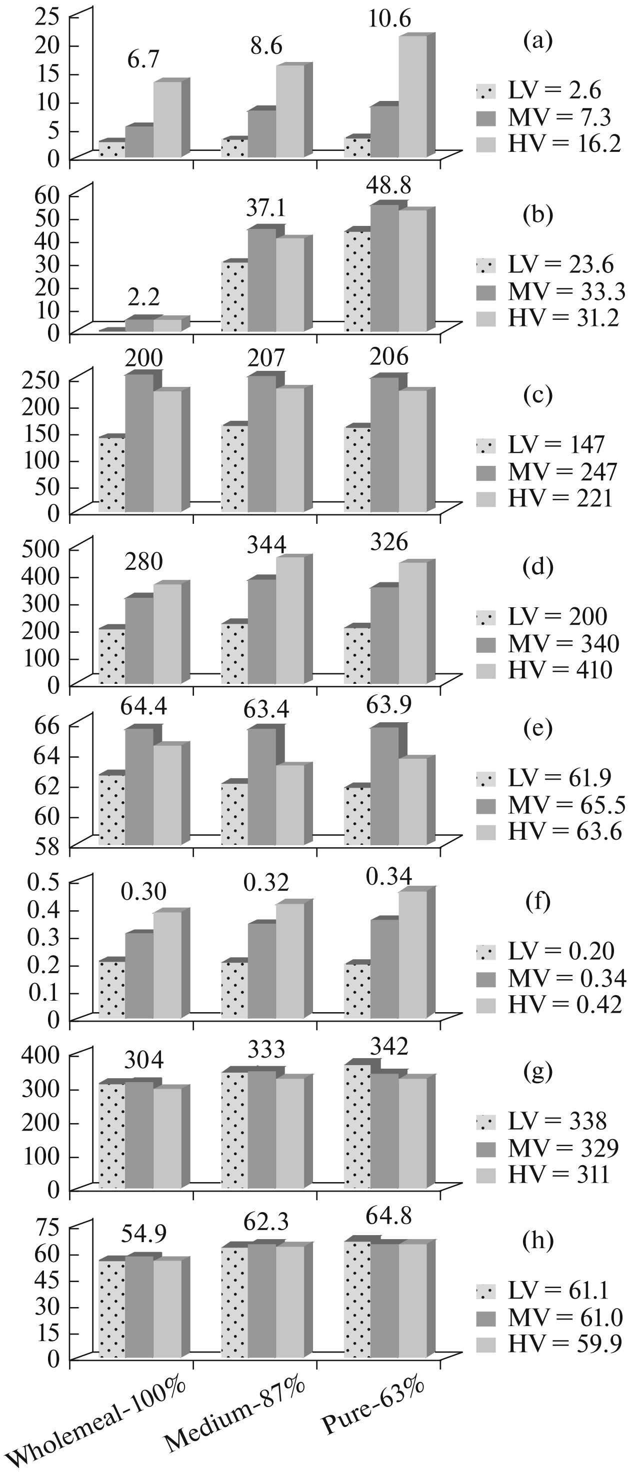


**Fig. 1.** Dynamics of grain quality traits depending on flour yield and WEV (according to the average data for LV, MV, and HV populations of the Al'fa and Moskovskaya 12 cultivars for 2015–2016); (a) water extract viscosity, cP; (b) flour whiteness, units; (c) falling number, s; (d) amylogram height, a. units; (e) gelatinization temperature, °C; (f) the H/D ratio; (g) bread volume, $cm^3$; (h) crumb porosity, %.

no correlation between WEV and FN, which is evidenced by the nature of the dynamics of the attributes (Fig. 1). The falling number correlated the best with the maximum starch gelatinization temperature ($r$ = 0.81 ± 0.05).

*Amylogram height.* The character of the dynamics of this trait, depending on the flour yield, largely corresponded to the dynamics of the WEV trait (Fig. 1d), since not only starch but also other swelling substances, such as pentosans and proteins present in flour, affect the amylograph's highest viscosity point. As the yield of flour decreased, the activity of alpha-amylase decreased, as evidenced by the increasing amylogram height. Thus, on average in two cultivars, it was 280 units for wholemeal flour, 344 units for medium flour, and 326 units for pure flour. Apparently, medium flour had the highest value of this trait, which can be explained by the fact that it had the most optimal ratio of the main components of swelling, namely starch, pentosans, and proteins, while wholemeal flour was inferior to other grades. The possible reason for the decrease in the amylogram in pure flour versus medium flour is a low content of protein in it. The relationship between the amylogram and WEV was positive. The lowest amylogram was characteristic of LV populations (200 units on average in two cultivars), it increased to 340 units in MV populations, and the highest amylogram was characteristic of HV populations: 410 units. This is because the LV populations contain little water-soluble pentosans, which protect the starch well from the amylase attack. The results of this process confirm the low values of the amylogram and the falling number. The grain of HV populations contains lots of WSPs with a higher water-absorbing capacity than in proteins. Due to this property, they inhibit the starch gelatinization process and positively influence the high viscosity point on the amylograph.

*Starch gelatinization temperature.* This indicator is considered the best criterion for evaluating the activity of the alpha-amylase enzyme than the amylogram height, since it takes into account the influence of the quantity and quality of starch. If starch contains many small starch grains from the outer layers of the endosperm, which inhibit gelatinization, their destruction requires higher temperatures. The dynamics of this trait was similar not with the height of the amylogram but with the falling number (Fig. 1d). As the percentage yield of flour increased, the peak gelatinization temperature remained unchanged, although the height of the amylogram increased. On average for the two cultivars, this peak was achieved at 64.4°C for wholemeal flour, 63.4°C for medium flour, and 63.9°C for pure flour. Since the percentage of flour yield did not significantly affect the activity of amylolytic enzymes of grain, a slight decrease in temperature in cultivars of pure and medium flours could be due to the qualitative difference between their starch contents but not enzymes. This difference consists in the fact that these flour grades contain relatively few starch grains from the outer layers of the endosperm, which are more resistant to the amylase attack. Their enzymatic destruction requires higher temperature [13]. The level of WEV caused a stronger dynamics of the gelatinization temperature than the flour yield. The lowest gelatinization temperature was observed in relatively low-starch LV populations (61.9°C) and the highest in high-starch MV populations (65.5°C). Starch of flour from the HV populations was gelatinized at a lower temperature (63.6°C), which can be explained by the low content of starch. Thus, in the process of divergent selection, LV populations correlatively gravitated toward a lower starch gelatinization temperature, while the HV populations gravitated toward a higher one.

*The H/D ratio.* This indicator makes it possible to evaluate the shape stability of toppling bread. In our experiments, this ratio in many respects corresponded to the dynamics of WEV and the amylogram height (Fig. 1f). As the percentage yield of flour decreased, the H/D ratio increased from 0.30 for wholemeal flour to 0.34 for pure flour. This was to be expected, since pure flour is dominated by starch from the deep layers of the endosperm, where WSP with a high water absorption capacity are concentrated. In wholemeal flour, the share of this starch is lower, and the viscosity of the rye dough is also lower; in proofing, it spreads out, as shown by the H/D ratio. With an increase in the rye flour yield, the H/D ratio tends to rise. The level of WEV caused a stronger impact on its dynamics than the flour yield. The lowest shape stability of bread was characteristic of LV populations (H/D = 0.20), and the highest one was characteristic of HV populations (H/D = 0.42). Obviously, the reason for such a contrast in the shape stability of toppling bread was the correlation effect of selection for WEV. This is confirmed by a high correlation between the H/D ratio and WEV ($r$ = 0.84 ± 0.07).

*Volumetric yield of bread.* The dynamics of this indicator strongly depends on the viscosity of the rye dough, which it gains due to WSPs. At high viscosity, it is able to retain more water and has a better shape stability, but the baked bread has a smaller volumetric yield. An important role is played by the activity of the alpha-amylase enzyme in flour. If it is high, the water-retaining capacity of the dough is reduced and the baked bread has a sticky crumb and a smaller volume. The yield of flour during grinding negatively affects the volumetric yield of bread (Fig. 1g). The bread from wholemeal flour had a very low volumetric yield (304 $cm^3$), while it increased to 333 $cm^3$ in the bread from medium flour and to 342 $cm^3$ from pure flour. The high potential of WEV contributed to a decrease in the volumetric yield of bread: it was the lowest (311 $cm^3$) in HV populations and the highest (338 $cm^3$) in LV populations. This is due to the influence of WSPs, which strongly absorb moisture. Their highest content was in pure flour from grain of the HV

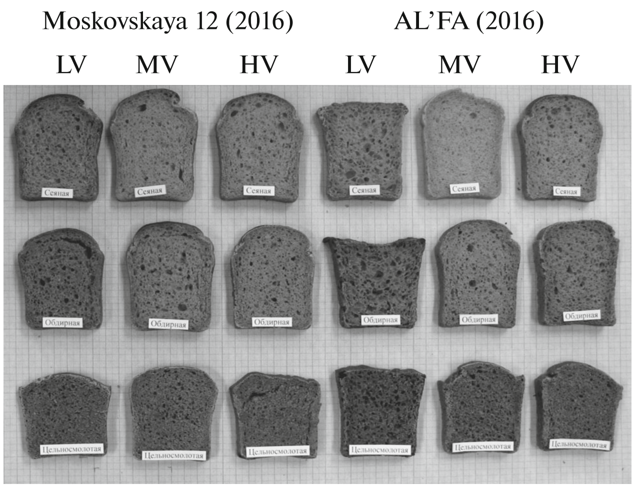


**Fig. 2.** Cross sections of panned loaf from the grain of LV, MV, and HV populations harvested in 2016 (upper row, pure flour; middle row, medium flour; lower row, wholemeal flour).

populations, and the viscosity of the dough was the highest possible.

*Porosity of crumb.* The percentage yield of flour adversely affected the porosity of the crumb of the panned loaf (Fig. 1 h). The most low-porous bread was obtained from wholemeal flour (54.9%), while the most highly porous bread was obtained from pure flour (64.8%). This is to be expected, since pure flour is characterized by a high content of starch, which swells better. The content of this starch in wholemeal flour is less, so the bread has a dense consistency, weak elasticity, and small pores (Fig. 2). Unlike the yield of flour, the WEV level did not significantly affect the porosity of the crumb. The average value of this indicator varied only slightly: 59.9% in HV populations, 61.0% in MV populations, and 61.1% in LV populations. Therefore, we can only talk about the tendency of the negative effect of viscosity on the porosity of the crumb. The higher porosity of the crumb in LV populations is explained by the relatively small, low-starch grain with low nature, which contains little WSPs. During hydrolysis, such starch forms many dextrins that poorly swell in water, to bind which there are not enough pentosans. As a result, the state of the bread crumb deteriorates and it becomes large-porous, sticky, and moist even with the normal bread moisture.

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