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THE FORMATION OF PRODUCTIVITY OF GRAIN CROPS WITH INTRODUCING HYDROGELS UNDER MODEL SOIL DROUGHT AND IN FIELD CONDITIONS

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Abstract

The use of water-absorbing hydrogels capable to regulate the soil water regime allows for a significant increase in crop production in arid and semi-arid climatic zones. Polyacrylamide and polyacrylonitrile hydrogels cyclically (over several years) absorb and release moisture, so they are most effective in agriculture. This paper shows that three polymer gels of different origin have similar effect on the yield structure and productivity of grain crops compared under controlled soil drought and in field tests. Domestic gels had the greatest effect on the 1000-grain weight. The type of hydrogel (either sodium or potassium base) did not significantly influenced the yield structure parameters. This work aimed to evaluate grain crops' productivity and yield structure as affected by polymer gels V-415 K and Ritin-10 (Russia) under simulated soil drought compared to the polymer Aquasorb (France) under field conditions of a zone of insufficient moisture. Microfield trials were performed on spring barley (*Hordeum vulgare* L.) cv. Leningradsky in 2015, spring wheat (*Triticum aestivum* L.) cv. Daria in 2016 and spring barley cv. Ataman using bottomless pots (Agrophysical Institute, Menkovsky branch, Leningrad Province) of a 0.075 m^2 area and a 0.0025 m^3 volume. The pots were filled with sod-podzolic sandy loamy soil according to the soil horizons' order. The treatments were a control ($N_{90}P_{90}K_{90}$); $N_{90}P_{90}K_{90}$ + Ritin-10 at 10-12 cm depth; $N_{90}P_{90}K_{90}$ + V-415 K at 10-12 cm depth; $N_{90}P_{90}K_{90}$ + Ritin-10 at 20-22 cm depth; $N_{90}P_{90}K_{90}$ + V-415 K at 20-22 cm depth. The dose of each hydrogel was 4 g/m^2, the seeding rate was 50 pcs/pot. Soil moisture in the pots was measured twice a week to calculate necessary watering rate. The effect of soil drought (55-60 % water holding capacity) was assessed from the tillering phase to full ripeness. The productivity of winter wheat (*T. aestivum*) cv. Steklovidnaya 24 as influenced by polymer gel Aquasorb (SNF s.a.s., France) was studied in the Republic of Kazakhstan in 2015-2017 (experimental fields of the Kazakh Research Institute of Agriculture and Plant Growing). Two doses of the absorbent (20 and 40 kg/ha) and their combination with nitrogen supplementation (N_{45}) were tested. The total number of plants per pot (per 1 m^2 in field trials), the number of productive plants, and productive bushiness coefficient, the ear length, the number of grains per ear, the grain mass per ear, and the 1000-grain weight were determined. The grain yield under a controlled "drought" when the hydrogels were introduced into the root layer (10-12 cm) differed slightly from the control (an increase by only 3-4 %). For the 20-22 cm depth, the yield exceeded the control by 25.0-27.7 % ($p < 0.01$). The hydrogels significantly influenced the yield structure parameters for productive bushiness coefficient, the number of grains per ear and the 1000-grain weight. With Ritin-10 hydrogel, the yield inversely correlated with the number of productive stems ($r = -0.83$), the number of grains per ear ($r = -0.78$) and the grain weight per ear ($r = -0.78$). With V-415 K, the correlation coefficients showed a close relationship between yield and tillering ($r = 0.70$), with the grain mass per ear ($r = 0.74$) and with the 1000-grain weight ($r = 0.71$). Under the simulated soil drought, the hydrogels had the greatest impact on the 1000-grain weight. Under field conditions of Kazakhstan, the yield of winter wheat largely depended on weather conditions. In a dry 2015, the hydrogel at a dose of 40 kg/ha with nitrogen fertilizers increased the crop yield by 6.6 c/ha compared to the control. The hydrogel together with nitrogen fertilizers also significantly ($p < 0.05$) increased the crop yield in a moderately wet 2016; in a wet 2017, the grain yield increased significantly ($p < 0.01$), up to 16.4-23.8% depending on the dose of the hydrogel. Aqusorb gel significantly affected all elements of yield structure. In the semi-arid period, when 20 kg/ha of Aquasorb hydrogel was applied, there was an inverse correlation between the yield and the grain mass per ear ($r = -0.99$) and the 1000-grain weight ($r = -0.98$). For a dosage of 40 kg/ha, there was a close correlation with the number of grains per ear ($r = -0.99$) and the grain mass per ear ($r = -0.87$). Wheat yield also had a close inverse relationship with the number of grains per ear ($r = -0.83$) when Aquasorb (20 or 40 kg/ha) was used with nitrogen fertilizers. In humid and moderately humid years, the dependence of yield on yield structure indicators is also strong ($r = 0.84$-0.99). Thus, the hydrogel introduced into the 10-12 cm soil layer dries out without watering and does not act as a water-retaining soil additive. A significant increase in the grain yield can be obtained by laying polymer gels to a depth of 20-22 cm after water-charging irrigation of the arable layer. In field conditions, during dry growing seasons, it is necessary to apply a high dose of hydrogel (40 kg/ha) in combination with nitrogen fertilizers. In moderately humid and humid growing seasons, a dose of 20 kg/ha is sufficient in combination with nitrogen fertilization.

Keywords: polymer gel, soil drought, water stress, barley, spring wheat, winter wheat, yield

Humidity is a limiting factor in growing crops. Plants that lack moisture lag behind in development, are more susceptible to diseases and pests, and do not compete well with weeds, which affects yields [1-3].

Moisture-absorbing polymer gels are used in various sectors of the national economy. In crop production and agriculture, they allow you to regulate the water regime of soils in arid and semi-arid climatic zones. Due to the network structure of the macromolecule, the hydrogel can accumulate a large amount of water in its volume [4, 5]. Water-absorbing polymer gels sorb melt or rain water, and in case of drought slowly release moisture (that is, they use the condensate of subsoil water vapor), nourishing the plants. Depending on the swelling capacity of the hydrogel, the amount of absorbed water can increase by 1000-1500% [6]. During swelling, there is no strong binding of water to the polymer molecule, so water remains available for plants [7].

Polyacrylamide and polyacrylonitrile hydrogels have the ability to cyclically (over several years) absorb and release moisture, so their use is most effective in agricultural activities [8]. Biopolymers are especially attractive for agriculture because they are biodegradable [9]. Some bacteria produce enzymes capable of converting biopolymers into water, carbon dioxide, methane, and biomass [9, 10].

Nutrients necessary for good plant growth (macronutrients N, P, K, Ca, Mg, S, micronutrients B, Cl, Co, Cu, Fe, Mn, Mo, Ni, Zn) are often not available in sufficient quantities in the environment. Polymeric materials can be used to deliver agrochemicals to the soil without causing pollution [11-14]. It has been shown that it is best to introduce nutrients into the polymer in the form of complex compounds (chelates), which are difficult to decompose into ions and cannot affect the decrease in the water absorption capacity of the polymer gel [15, 16]. By reducing losses due to gravity and physical evaporation, the hydrophilic polymer retains an additional supply of moisture in the soil profile [17, 18]. Hydrogels improve soil agrophysical properties [18, 19].

Plants, both in their natural environment and during cultivation, are often subjected to environmental stress [8, 20]. Water-absorbing polymer gels are very effective in conditions of elevated temperature and soil moisture deficiency [20-22]. The lack or excess of heat or moisture during certain periods of ontogenesis significantly affects the growth and development of plants, as well as the yield and quality of grain. When hydrogels are introduced into the root-inhabited soil layer, an additional supply of moisture is created, which is necessary during critical periods of development (tillering — stem elongation). L.O. Ekebafe et al. [23] and G. Cheruiyot et al. [24] confirmed that polymers help maintain soil moisture by changing the distribution of soil particles, liquid and gas phases when water is added, which increases the proportion of liquid compared to gas.

A high percentage of moisture retention when using a hydrogel during the period of active growth contributes to a high intensity of photosynthesis [9, 25]. In addition, by reducing water stress throughout the growing cycle, the use of polymers improves crop quality [20, 22, 26]. R. Hayat et al. [27] found that the amount of water absorbed by the polymer affected yield parameters. The lack of moisture in the soil during the period of grain filling significantly affects the structure of the crop and the overall productivity of plants. Adding a moisture-swellable polymer to the soil increased the 1000-grain weight in corn and soybeans [28] and the yield in corn and winter wheat [23, 29]. J. Grabinski et al. [30] note that the presence of hydrogel in the soil has an insignificant effect on the number of plants, but the effect on the number of grains per ear and the 1000-grain weight was more significant. The 1000-grain weight is also affected by meteorological factors and agricultural practices [20, 27, 29].

Many arid and semi-arid regions face problems with uncertain and insufficient rainfall [8, 23, 31, 32]. In arid climatic zones, the use of polymer gels in sandy soil (macroporous medium) seems to be one of the most significant methods for increasing its water-retaining capacity and increasing crop productivity. Hydrogel particles can serve as miniature "reservoirs" of water in the soil. Water will flow from them at the request of the root hairs through the osmotic pressure difference. Hydrogels provide the retention and release of nutrients as they are absorbed. Consequently, the plant can access fertilizers which improve crop growth and productivity [31, 32-35].

Studies on the effect of Sky Gel polymer gel (Imec®, SkyGel®, Mebiol Gel®, Mebiol, Inc., Japan) on the growth, yield and water loss of wheat plants in Iraq, showed that 4, 8 and 12% Sky Gel added to the soil ncreased in the number of grains per spike to 48.94, 50.03 and 51.93 vs. 45.26 in the control. The 1000-grain weight increased when the gel amount increased. The highest value (4.11 g) occurred with 12% gel, the lowest (3.43 g) in the control. When 12% Sky Gel was applied, the maximum plant height (87.33 cm), root length (24.58 cm), root shoot coefficient (28.15), yield (4.83 t/ha) and the highest efficiency of water use (1.516 kg/m^3) were noted [36].

Hydrogel Ritin-10 (sodium base) (OOO RITEK-ENPC, Elektrogorsk, Russia) is a cross-linked copolymer of polyacrylamide [3, 18]. Studies conducted in the zone of unstable moisture in the conditions of the Central Caucasus showed that the introduction of this hydrogel into the root layer (10-12 cm) gives a positive effect only in years with sufficient soil moisture. In dry years, it is preferable to apply the hydrogel to a depth of 20-22 cm [2]. Hydrogel V-415 K (potassium base) (ZAO Biokatalysis, Saratov, Russia) is a cross-linked copolymer of acrylic acid acrylamide [3, 18].

This paper shows that Russian-made hydrogels are as effective as foreign polymer gels in terms of their effect on productivity and structural elements of grain crops under model soil drought. The greatest effect of domestic gels had on the 1000-grain weight. The type of hydrogel (with sodium or potassium base) did not significantly affect the crop structure.

The purpose of the work is to evaluate the effect of Russian polymer gels V-415 K and Ritin-10 on the productivity and structure of the crop yield under simulated soil drought in comparison with the foreign polymer Aquasorb which was used in the field conditions of a zone of insufficient moisture.

Materials and methods. The microfield vegetation experiment was carried out on spring barley (*Hordeum vulgare* L.) cv. Leningradsky in 2015, spring wheat

(*Triticum aestivum* L.) cv. Daria in 2016, and spring barley cv. Ataman in 2017 in a “dryer” installation (Agrophysical Research Institute, Menkovsky branch, Leningrad Province). The dryer consists of a metal frame (frame) with installed light-transmitting polycarbonate, which allows simulation of the moisture supply of the experimental site by excluding the impact of external precipitation. To avoid the influence of atmospheric precipitation, a ditch was laid around the dryer (30-35 cm width, 60-70 cm depth). The depth of the dryer is 2 m, the total area is 50 m^2, 15 m^2 were used in the experiment. To isolate the roots from groundwater, two layers of a plastic film was laid on the bottom. Atmospheric and soil droughts are modeled in arid areas during dry periods of vegetation, and soil droughts during wet periods [22].

The soil in the experiment was soddy-podzolic sandy loam, sandy loam granulometrically, with sandy moraine parent rock and loamy moraine underlain. The total content of fine dust fractions and silt fractions did not exceed 6%. The soil contained 5% physical clay (particles less than 0.01%) and 95% physical sand particles. Soil density was from 1.03 to 1.07 g/cm^3, with 9.4-10.6 m^2/g specific surface, 0.54-0.55% hygroscopic moisture, 2.95% humus; the sum of absorbed bases is 6 meq/100 g of soil. The pH in the upper layers was from 4.95 to 5.03 and decreased with depth. Phosphorus and potassium contents were sufficient [18, 37].

Bottomless pots (0.075 m^2/0.0025 m^3) were filled with soil with regard to soil horizons. The experimental design was as follows: control (the basal level of $N_{90}P_{90}K_{90}$); $N_{90}P_{90}K_{90}$ + Ritin-10 (application depth 10-12 cm); $N_{90}P_{90}K_{90}$ + V-415 K (10-12 cm); $N_{90}P_{90}K_{90}$ + Ritin-10 (20-22 cm); $N_{90}P_{90}K_{90}$ + V-415 K (20-22 cm). The hydrogel (4 g/m^2) was placed at various depths in the pots, the seeding rate was 50 grains per pot, with a 5-fold repetition under systematic layout.

Soil moisture in the pots was measured with a soil moisture meter MG-44 (OOO Vetinstument, Russia) twice a week, and the irrigation rate was calculated according to the readings. At the beginning of the growing season, the soil moisture in the pots at the dryer was 70% of the lowest moisture capacity (LW). The effect of soil drought (55-60% HB) on plant growth and development was assessed from the tillering phase to full ripeness [38].

The productivity of winter wheat (*Triticum aestivum* L.) variety Steklovidnaya 24 under the influence of Aquasorb polymer gel (SNF s.a.s., France) was studied in the experimental fields of the Kazakh Research Institute of Agriculture and Plant Growing (Republic of Kazakhstan) in 2015-2017.

The soil of the experimental fields is light chestnut light loamy, coarse-silty medium loam in mechanical structure, being 39-42% physical clay, 45-51% coarse dust, and 12-17% silt. The content of carbonates was 2.7-3.6% in the upper layers and 6.5% in the carbonate horizon, pH 8.2-8.8. The sum of absorbed bases did not exceed 12 meq/100 g of soil. Calcium accounted for 80-90%, magnesium for 10-20%. The provision of the soil with readily hydrolysable nitrogen is medium, with mobile phosphorus is low, and with exchangeable potassium is medium. The sum of salts in the upper layer did not exceed 0.12%. In the upper horizon, the soil contained 2.02% humus, 0.12-0.14% gross nitrogen. Water-physical properties were characterized as follows: 2.62-2.72 g/cm^3 specific gravity, 1.23-1.35 g/cm^3 bulk density, and 50-53% porosity. The moisture content of stable wilting is 6-8% [7, 21].

Two doses of absorbent (20 and 40 kg/ha) and their combination with nitrogen supplementation (N_{45}) were tested (the control was without absorbent and nitrogen fertilizers). The repetition of the experiment is 4-fold, the placement of variants is systematic [32]. Phenological and biometric observations were done as per the methodology of field experiments [39].

The yield structure of the studied crops was determined by the sheaf selection method according to the following indicators: the total number of plants per growing vessel (in field conditions per 1 m^2), the number of productive plants, and productive tillering. Structural analysis of the ear was carried out according to the length of the ear, the number of grains in the ear, the mass of grain from one ear, and the 1000-grain weight.

Statistical data processing was performed using one-way analysis of variance (ANOVA) and correlation analysis using the Statistics 5.0 program (StatSoft, Inc., USA). Means (M) and standard errors of the means (±SEM) were calculated. Differences were considered statistically significant at $p \leq 0.05$.

Results. In the dryer [38], the hydrogel, when introduced into the root layer (10-12 cm), had a beneficial effect only with the early emergence of seedlings of the studied crops. With the polymer placed at a depth of 20-22 cm, the soil moisture in the growing vessels corresponded to the lowest moisture capacity [3].

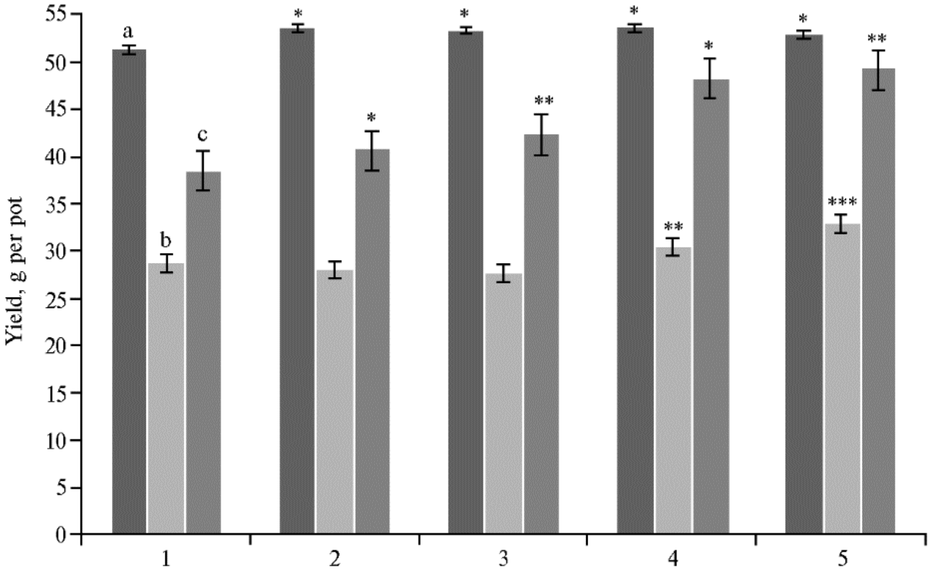

Fig. 1. Yields of spring barley (*Hordeum vulgare* L.) cv. Leningradsky (2015) (a)**, spring wheat (*Triticum aestivum* L.) cv. Darya** (2016) (b)**, spring barley cv. Ataman** (2017) (c) **under simulated soil drought as influenced by domestic polymer gels introduced into the soil at various depths:** 1 — control ($N_{90}P_{90}K_{90}$), 2 — $N_{90}P_{90}K_{90}$ + Ritin-10 (10-12 cm), 3 — $N_{90}P_{90}K_{90}$ + V-415 K (10-12 cm), 4 — $N_{90}P_{90}K_{90}$ + Ritin-10 (20-22 cm), 5 — $N_{90}P_{90}K_{90}$ + V-415 K (20-22 cm) (n = 5, M±SEM; test at a field “dryer” installation, Agrophysical Research Institute, Menkovsky branch, Leningrad Province).

*, **, *** Difference between the treatment and control is statistically significant at $p < 0.05$, $p < 0.01$, and $p < 0.001$, respectively.

The use of hydrogel in the dry land in 2015 slightly increased the yield of Leningradsky barley compared to the control (by 3-4%, $p < 0.05$) (Fig. 1). The yield of cv. Daria in 2016 (see Fig. 1) was higher than the control only when both types of hydrogels were placed at a depth of 20-22 cm. For V-415 K and Ritina-10, the differences were statistically significantat at $p < 0.001$ and $p < 0.01$, respectively; Ritin-10 and V-415 K increased the yield by 5.9 and 14.6%, respectively. In 2017, the yield of barley cv. Ataman (see Fig. 1) changed slightly when gels were placed in the root zone (10-12 cm), with Ritin-10 by 5.6%, with V-415 K by 9.9 % above control. When applied to a depth of 20-22 cm, a 25.0-27.7% increase in yield was statistically significant ($p < 0.05$) for both treatments in the test (see Fig. 1, Table 1).

1. Yield components in grain crops under simulated soil drought as influenced by domestic polymer gels introduced into the soil ($n = 5$, M±SEM; test at a field “dryer” installation, Agrophysical Research Institute, Menkovsky branch, Leningrad Province)

Treatment	Productive stems per pot	Productive tillering	Grains per ear	Weigh, g		Yield	
				gains per ear	1000 gains	g per pot	Δ vs. control, %
Spring barley (*Hordeum vulgare* L.) cv. Leningradsky (2015)							
Control	48±2	1.18±0.08	31±3	0.98±0.51	37.0±0.93	51.3±0.4	
Ritin-10 (10-12 cm)	53±3	1.21±0.09	30±2	1.06±0.61	36.0±0.95	53.5±0.5*	4.3
V-415 K (10-12 cm)	55±3	1.22±0.09	29±2	0.83±0.50	37.5±0.76	53.3±0.5*	3.9
Ritin-10 (20-22 cm)	56±3	1.23±0.09	33±3	1.15±0.57	38.0±0.80	53.5±0.5*	4.3
V-415 K (20-22 cm)	57±2	1.25±0.09	35±2	1.17±0.57	38.0±0.79	53.0±0.5*	3.3
Spring wheat (*Triticum aestivum* L.) cv. Darya (2016)							
Control	48±2	1.14±0.07	24±2	0.52±0.63	29.0±1.71	28.7±0.5	
Ritin-10 (10-12 cm)	52±3	1.20±0.08	22±3	0.47±0.42	27.0±2.12	28.0±0.4	–2.4
V-415 K (10-12 cm)	54±3	1.28±0.08	27±2	0.89±0.57	33.5±1.51	27.7±0.5	–3.5
Ritin-10 (20-22 cm)	52±2	1.18±0.09	29±2	1.03±0.50	36.0±1.03	30.4±0.6**	5.9
V-415 K (20-22 cm)	56±2	1.30±0.09	28±2	0.92±0.32	34.0±1.10	32.9±0.4***	14.6
Spring barley (*Hordeum vulgare* L.) cv. Ataman (2017)							
Control	43±2	1.10±0.08	19±3	0.83±0.22	47.0±0.66	38.5±0.6	
Ritin-10 (10-12 cm)	42±3	1.13±0.09	19±2	0.77±0.18	52.1±0.50	40.6±0.5*	5.5
V-415 K (10-12 cm)	46±2	1.12±0.09	19±2	0.82±0.21	49.0±0.56	42.3±0.6**	9.9
Ritin-10 (20-22 cm)	47±2	1.12±0.08	20±3	0.94±0.18	55.1±0.46	48.2±0.6*	25.2
V-415 K (20-22 cm)	47±2	1.12±0.09	20±3	1.04±0.17	52.0 ±0.56	49.1±0.6**	27.5

Note. $N_{90}P_{90}K_{90}$ is a basal fertilizer level. For the analysis, we partially used the data obtained by us earlier (38).

*, **, *** Difference between the treatment and control is statistically significant at $p < 0.05$, $p < 0.01$, and $p < 0.001$, respectively.

During the active vegetation in 2015 (May-August), the average daily temperatures were slightly higher than the long-term average, only in July the air temperature was below the norm by 2.3 °C. In May, 91% of precipitation fell from the climatic norm, in June, there was 58.5% precipitation, in July 114.8% (slightly above the norm), in August — 42%. The lack of moisture was felt in almost all phases of development of spring barley (HTC = 1.5 during tillering-flowering period, HTC = 1.6 during grain filling). Only the effect of hydrogel contributed to the yield increase from 3.3 to 4.3%. In simulated soil drought, the yield components of Leningradsky variety was the best with sodium- and potassium-based hydrogels placed at a 20-22 cm depth. Productive tillering coefficient (1.23 and 1.25), the number of grains per ear (33 and 35), the weight of grain per ear (1.15 and 1.17 g) and the 1000-grain weight (38 g) exceeded the control values (see Table 1). In 2016, the average daily air temperature of the growing season slightly exceeded the norm, by 3 °C in May, by 0.8 °C in June, by 1 °C in July, and by 1.1 °C in August. Rainfall was uneven: in May there was a significant lack of precipitation, in June 116% of the norm fell, in July 131%, and in August 187%. During sowing-tillering HTC = 0.6; during the growth and development of spring wheat (tillering-flowering) HTC = 2.3. This affected the yield and indicators of the structure of the harvest of spring wheat cv. Daria. When Ritin-10 hydrogel was applied to a depth of 10-12 cm, the yield structure indicators were lower than in the control and in the variant with V-415 K. The best indicators (1000-grain weight, number of grains per spike, productive tillering) occurred at a gel application depth of 20-22 cm (see Table 1). Temperatures in May 2017 were 2.0-5.0 °C below the norm, 31% of precipitation fell from the monthly norm. The deviation of the average monthly air temperature in June from the climatic norm was 2.0-4.0 °C, the monthly precipitation amounted to 93.6%. In July, the average monthly air temperature was also 2.0-3.6 °C above the norm, the amount of precipitation coincided with the climatic norm. The average monthly temperature in August was 0.4 °C higher than the average long-term vaues, 148% of precipitation fell. The year was not very favorable for the growth and development of spring barley cv. Ataman.

When using the hydrogels Ritin-10 and V-415 K in the root zone, the parameters of the yield structure did not differ significantly from the control. Productive tillering was 1.10 in the control, and 1.12-1.13 in the variants with hydrogel. The number of grains in the spike both in the control and in the variants with hydrogel was 19 pcs. The application of hydrogels to a depth of 20-22 cm significantly increased the 1000-grain weight, 55.1 g with Ritin-10 and 52.0 g with V-415 K vs. 47.0 g in the control (see Table 1).

An analysis of the correlations between the components of yield structure (Table 2) showed that under the conditions of simulated soil drought, when Ritin-10 hydrogel was introduced into the upper root layer, the yield of grain crops closely correlated with productive tillering (r = 0.72), weight grains from an ear (r = 0.62) and 1000-grain weight (r = 0.88). Yield had an inverse correlation with the number of productive stems (r = –0.64) and a weak correlation with the number of grains per ear (r = 0.47). When placing the Ritin-10 gel in a layer of 20-22 cm, the correlation coefficients showed a close relationship between the yield and all elements of the crop structure. Productivity was inversely correlated with the number of productive stems (r = –0.83), the number of grains per ear (r = –0.78) and the mass of grain per ear (r = –0.78). When applying polymer V-415 K to a depth of 10-12 cm, a close correlation was noted between crop yields and productive tillering (r = 0.99), grain weight per ear (r = 0.89) and 1000-grain weight (r = 0.63); a weak relationship was established with the number of grains per ear (r = 0.43). When placing the B-415 K gel at a depth of 20-22 cm, a less close dependence of yield on the number of productive stems (r = 0.58) and grains per ear ($r = 0.58$) and a close relationship with productive tillering ($r = 0.70$), the grain weight per ear ($r = 0.74$) and 1000-grain weight ($r = 0.71$). The critical value of r at the 5% significance level is 0.63. The main elements of the crop structure, on which hydrogels had a significant effect under the conditions of simulated soil drought, are productive tillering, grain weight per ear, and 1000-grain weight.

2. Correlation coefficients (*r*) between grain yield and yield components under simulated soil drought as influenced by introduced domestic polymer gels into the soil ($n = 5$, M±SEM; test at a field "dryer" installation, Agrophysical Research Institute, Menkovsky branch, Leningrad Province, 2015-2017)

Productive stems	Productive tillering	Grains per ear	Grain weigh per ear	1000-grain weight
		Y = f (control)		
–0.79*	–0.80*	–0.73*	–0.68*	–0.63
		Y = f (Ritin-10, 10-12 cm layer)		
–0.64*	0.72*	0.47	0.62	0.88*
		Y = f (Ritin-10, 20-22 cm layer)		
–0.83*	0.77*	–0.55	–0.81*	0.62
		Y = f (V-415 K, 10-12 cm layer)		
0.75*	0.99*	0.43	0.89*	0.63
		Y = f (V-415 K, 20-22 cm layer		
0.58	0.70*	0.58	0.74*	0.71*

Note. Spring barley (*Hordeum vulgare* L.) cv. Leningradsky was grown in 2015, spring wheat (*Triticum aestivum* L.) cv. Darya in 2016, spring barley (*H. vulgare* L) cv. Ataman in 2017.

* Correlation coefficients are statistically significant at $p = 0.05$ (critical r value at 5% significance level is 0.63).

Therefore, under the conditions of simulated soil drought, the hydrogel placed to the soil root layer (10-12 cm) dried out and did not act as a water-retaining soil additive. The yield of grain crops increased statistically significantly ($p < 0.05$) when gels were placed at a depth of 20-22 cm. That is, in order to increase the productivity of grain crops in conditions of soil drought, it is necessary to apply hydrogel to the depth of the arable layer of 20-22 cm with preliminary moisture-charging irrigation before sowing [3, 38].

In the Republic of Kazakhstan, experiments on winter wheat cv. Steklovidnaya showed that the effect of Aquasorb hydrogel depends on meteorological conditions. The moisture supply of plants is largely determined by the amount of seasonal precipitation and the soil moisture reserves accumulated during autumn and winter. The lack of natural moisture reserves in the soil significantly reduces the yield of winter wheat [21, 29]. The southeast of Kazakhstan, where field trials were carried out, is a zone of rain-fed agriculture. During the growing season of grain crops (May-July), only 30-35% of the average annual precipitation falls there, the rest - in the post-harvest and cold periods of the year.

The grain yield in 2015 in the control was 27.0 c/ha. With Aquasorb at a dose of 20 and 40 kg/ha, the yield was 28.0 c/ha (3.7% increase) and 32.2 c/ha. (19.3%) (Fig. 2). Nitrogen fertilization contributed to an increase in yield in the control up to 27.9 c/ha. In experimental variants with hydrogel, this agrotechnical method statistically significantly ($p < 0.05$) increased the grain yield to 29.2 c/ha when applying the gel at a dose of 20 kg/ha and to 35.7 c/ha at 40 kg/ha. During the growing season of 2015, only 305 mm of precipitation fell, the year turned out to be moderately dry, so the influence of the hydrogel was undeniable. According to weather conditions, 2016 was moderately humid, which favorably affected the yield. It varied from 29.0 q/ha in the control to 32.5 q/ha (increase 12.1%) and 33.6 q/ha (15.9%) at a hydrogel dose of 20 and 40 kg/ha, respectively. Aquasorb in combination with fertilizing with nitrogen fertilizers increased the yield by 3.2 c/ha (10.0%, $p < 0.05$) and 5.4 c/ha (16.9%, $p < 0.01$), respectively, in the variants N45 + Aquasorb (20 kg/ha) and N45 + Aquasorb (40 kg/ha) (see Fig. 2).

3. Components of winter wheat (*Triticum aestivum* L.) cv. Steklovidnaya 24 yield as influenced by Aquasorb (Frnace) **polymer gel introduced into the soil** (*n* = 4, *M*±SEM; field test, zone of insufficient moisture of the Republic of Kazakhstan)

Treatment	Productive stems per pot	Productive tillering	Grains per ear	Weigh, g		Yield	
				gains per ear	1000 gains	c/ha	Δ vs. control, %
2015							
Control	345±1.3	1,72±0,2	27±1	0,98±0,10	40,4±0,4	27,0±0,60	
Aquasorb (20 kg/ha)	348±1.1	1,75±0,2	30±1	1,06±0,20	40,7±0,3	28,0±0,62	3,7
Aquasorb (40 kg/ha)	363±1.1	1,83±0,1	32±2	1,14±0,20	41,3±0,5	32,2±0,60**	19,3
Control + N_{45}	347±1.2	1,94±0,2	29±1	1,03±0,14	40,6±0,4	27,9±0,63	3,3
Aquasorb (20 kg/ha) + N_{45}	353±1.3	2,02±0,2	33±1	1,17±0,20	41,0±0,6	29,2±0,61**	8,2
Aquasorb (40 kg/ha) + N_{45}	377±1.5	2,10±0,2	35±1	1,22±0,13	41,7±0,5	35,7±0,60**	32,2
2016							
Control	353±1.2	1,83±0,2	30±1	1,04±0,12	40,9±0,4	29,0±1,07	
Aquasorb (20 kg/ha)	371±1.5	1,89±0,2	33±2	1,09±0,10	41,4±0,5	32,5±0,70*	12,1
Aquasorb (40 kg/ha)	380±1.4	1,93±0,1	34±2	1,15±0,20	41,9±0,6	33,6±0,70**	15,9
Control + N_{45}	365±1.4	1,98±0,2	33±1	1,08±0,10	41,5±0,5	31,9±1,10	10,0
Aquasorb (20 kg/ha) + N_{45}	388±1.5	2,04±0,1	34±1	1,18±0,20	42,0±0,5	35,1±0,60**	21,0
Aquasorb (40 kg/ha) + N_{45}	397±1.4	2,07±0,2	35±2	1,27±0,13	42,7±0,6	37,3±0,63*	28,6
2017							
Control	344±1.3	1,69±0,2	26±1	0,96±0,12	40,2±0,6	26,1±0,60	
Aquasorb (20 kg/ha)	352±1.2	1,75±0,2	28±1	1,05±0,10	40,8±0,6	28,2±0,60	8,0
Aquasorb (40 kg/ha)	362±1.1	1,81±0,2	31±2	1,15±0,13	41,4±0,5	31,9±0,50*	22,2
Control + N_{45}	351±1.2	1,78±0,2	27±2	1,01±0,20	40,6±0,6	28,1±0,60	7,7
Aquasorb (20 kg/ha) + N_{45}	366±1.1	1,87±0,2	32±1	1,17±0,14	41,6±0,5	32,7±0,56**	25,3
Aquasorb (40 kg/ha) + N_{45}	372±1.3	1,91±0,1	33±2	1,22±0,20	42,0±0,5	34,8±0,54**	33,3

*, ** Difference between the treatment and control is statistically significant at $p < 0.05$ and $p < 0.01$, respectively.

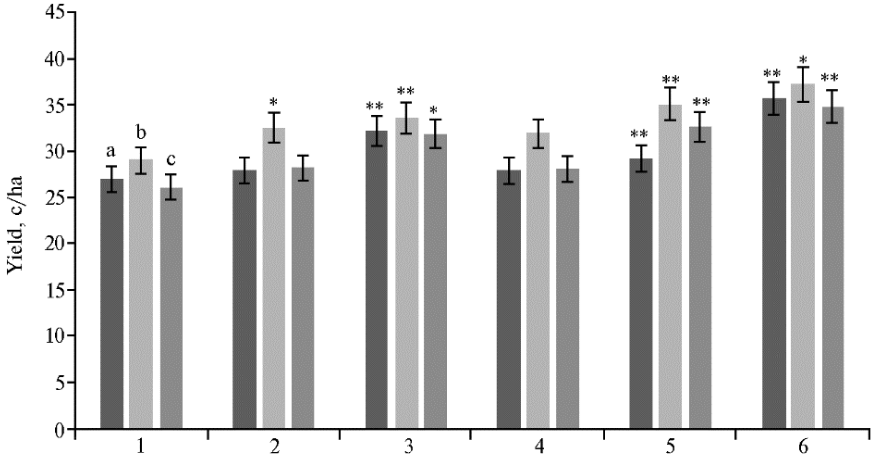

Рис. 2. Yieds of winter wheat (*Triticum aestivum* L.) cv. Steklovidnaya 24 in 2015 (a)**, 2016** (b), and **2017** (в) **as influenced by Aquasorb** (Frnace) **polymer gel introduced into the soil:** 1 — control (withoutabsorbent and nitrogen fertilizers), 2 — Aquasorb (20 kg/ha), 3 — Aquasorb (40 kg/ha), 4 — N_{45}, 5 — N_{45} + Aquasorb (20 kg/ha), 6 — N_{45} + Aquasorb (40 kg/ha) ($n = 4$, *M*±SEM; field test, zone of insufficient moisture of the Republic of Kazakhstan).
*, ** Difference between the treatment and control is statistically significant at $p < 0.05$ and $p < 0.01$, respectively.

Winter wheat yields in 2017 were lower than in 2015 and 2016 as 2017 was very wet (610.9 mm of rainfall). Yields significantly increased with hydrogel at a dose of 40 kg/ha ($p < 0.01$) and with gel doses of 20 and 40 kg/ha in combination with nitrogen supplementation ($p < 0.05$) (see Fig. 2). The increase in yield ranged from 8.0% to 22.2% without ferilizers, with fertilizers, it was in the range of 16.4-23.8% (Table 3).

In 2015, for the growing season of winter wheat, the sum of average daily temperatures was 2036.4 °C with 305.0 mm precipitation which exceeded the value of the long-term average data (231.6 mm) by 73.4 mm. In this year, which was characterized as moderately dry, nitrogen fertilization with N_{45} had a positive effect on the productive tillering with an increase in the index from 1.94 in control up to 2.02 and 2.10 (under Aquasorb doses of 20 and 40 kg/ha). At a dose of 20 kg/ha, the number of grains per ear increased from 27 to 32 without nitrogen fertilization and from 29 to 35 with nitrogen fertilization, grain weight per ear icreased from 0.98 g to 1.14 g and from 1.03 g to 1.22 g. respectively.

In 2016, due to the warm winter with little snow, active growth and development of plants was observed (average daily air temperature +12.9 °C, maximum +21.3 °C and minimum +4.8 °C). During the growing season, the sum of average daily temperatures amounted to 2126.2 °C, exceeding by 465.1 °C the long-term average values (1694.7 °C). Natural moisture reserves exceeded the 2015 level by 305.9 mm and the long-term average (231.6 mm) by 379.3 mm. Moisture conditions in 2016 were favorable, so winter wheat plants grew and developed actively, which provided them with high productive tillering (from 1.83 to 2.07), high grain number per ear (30 in control vs. 35 when applying hydrogel and fertilizers). At the same time, the weight of grain per ear was high - from 1.04 to 1.27 g. The weight of 1000 grains in the control was 40.9 g; 41.9 g, that is, the increase to the control amounted to 0.5 g and 1.0 g. During the spring nitrogen fertilization at a dose of 45 kg/ha, the formation of a grain mass of 41.5 g in the control and 42.0 and 42.7 g when adding hydrogel.

In 2017, there was slight heat deficit (1981.3 °C), especially in the spring months, due to a significant amount of natural precipitation (385.2 mm). In summer, on the contrary, the increased thermal regime, combined with a lack of precipitation, negatively affected the formation of the yield and grain quality. Due to the underdeveloped short ear, shrunk grains (from 26 to 33 pcs.) were formed. The grain weight per ear was the lowest in the control without fertilizers (0.96 g). The introduction of hydrogel at a dose of 20 kg/ha contributed to an increase in the weight of grain per ear to 1.05 g. An increase in the rate of hydrogel to 40 kg/ha ensured an increase in this indicator to 1.15 g. Nitrogen supplementation increased grain weight per ear from 1.01 g in control to 1.17 and 1.22 g. In general, grain weight per ear was the lowest compared to other years of research. Similarly to the indicator considered above, the 1000-grain weight also was the lowest compared to 2015 and 2016 and in the experiment ranged from 40.2 g in the control to 42.0 g in the test treatments at a hydrogel rate of 40 kg/ha and fertilizers.

Correlation analysis (Table 4) showed a close relationship between yield and yield components in the semi-arid period in all variants of the experiment. When applying 20 kg/ha of Aquasorb hydrogel to the soil, an inverse correlation occurred between the yield and the grain weight per ear (*r* = –0.99) and 1000-grain weight (*r* = –0.98), when applying 40 kg/ha. A close inverse relationship was established with the number of grains per ear (*r* = –0.99) and the grain weight per ear (*r* = –0.87). Wheat yield also had a close inverse relationship with the number of grains per spike (*r* = –0.83) in the Aquasorb polymer variants at the application rates of 20 and 40 kg/ha together with nitrogen fertilizers. In humid and moderately humid years, the dependence of yield on yield structure indicators was also strong (*r* = 0.84-0.99). In these years, the yield had a less close correlation with the number of grains per ear (*r* = –0.54; *r* = –0.59). The critical *r* value at the 5% significance level is 0.71.

4. Correlation coefficients (*r*) between grain yield and yield components in winter wheat (*Triticum aestivum* L.) cv. Steklovidnaya 24 as influenced by Aquasorb (Frnace) **polymer gel introduced into the soil** (field tests, zone of insufficient moisture of the Republic of Kazakhstan, 2015-2017)

Productive stems	Productive tillering	Grains per ear	Grain weigh per ear	1000-grain weight
		Y = f (control)		
0.83*	–0.87*	0.90*	–0.90*	–0.87*
		Y = f (Aquasorb, 20 kg/ha)		
0.99*	0.78*	0.87*	–0.99*	–0.98*
		Y = f (Aquasorb, 40 kg/ha)		
0.86*	0.64	–0.99*	–0.87*	0.99*
		Y = f (N_{45})		
0.84*	–0.92*	0.70	0.99*	0.94*
		Y = f (Aquasorb, 20 kg/ha + N_{45})		
0.69	0.91*	–0.83*	0.99*	0.99*
		Y = f (Aquasorb, 40 kg/ha + N_{45})		
0.77*	0.79*	–0.83*	0.98*	–0.80*

* * Correlation coefficients are statistically significant at p = 0.05 (critical *r* value at 5% significance level is 0,71).

Therefore, to increase the productivity of winter wheat, the Aquasorb absorbent should be used at a dose of 20 kg/ha in moderately humid and humid years and 40 kg/ha in moderately dry years in combination with early spring fpplication with nitrogen fertilizers.

Thus, our studies carried out under simulated soil drought showed that with hydrogel incorporated into the root layer (10-12 cm), the yield of grain crops differed slightly from the control (an increase of only 3-4%), while when the hydrogel was introduced to a depth of 20-22 cm, it was 25.0-27.7%. When using hydrogels, the productive tillering, the number of grains per ear, and, to the greatest extent, the 1000-grain weight changed significantly, and the weight of grain per ear and the 1000-grain weight had a great influence on the crop yield. In the experiments of N. Kilic et al. [29], it was noted that under arid conditions, the most sensitive indicator of the crop structure to high temperatures and drought is the number of grains per spike. A positive and significant correlation was established between the yield, the number of grains per ear and the weight of 1000 grains. Another study [36) showed that the addition of Sky Gel to the soil at doses of 4, 8 and 12% led to an increase in the number of grains per ear from 45.26 in the control to 48.94, 50.03 and 51.93 pcs. It was found that of 1000-grain weight increased due to an increase in the amount of Sky Gel, the highest value (4.11 g) was obtained when using Sky Gel at a dose of 12%, the lowest (3.43 g) in the control.

The increase in the effectiveness of the hydrogel with a deeper introduction into the soil, noted by us during controlled drought, indirectly indicates the dependence of its ameliorative properties on the water regime of the environment. This is fundamentally consistent with the data that we obtained in field experiments. In the zone of rain-fed agriculture in the southeast of Kazakhstan, when Aqusorb was applied to the root layer (10-12 cm), the effect of the hydrogel and the optimal modes of its application (doses and combination with nitrogen fertilizers) largely depended on the natural supply of moisture to the soil. The gel significantly affected all the studied elements of the structure of the winter wheat crop. J. Grabinski et al. [30] found that the yield of winter wheat largely depends on the weather conditions of the year under study and the dose of hydrogel. The highest yield was obtained when applying an increased dose (30 kg/ha) of the polymer. In addition, the authors note that the 1000-grain weight was significantly higher when treated with doses of 20 kg/ha and 30 kg/ha of hydrogel compared to minimum dose (10 kg/ha) and control. The use of the hydrogel did not affect the number of plants and the number of productive stems of winter wheat, but significantly increased the number of grains per ear, the 1000-grain weight and, consequently, the crop yield. Chinese scientists L. Yan et al. [26] found that the use of Aqusorb polymer in combination with nitrogen fertilizers could mitigate the effects of drought on winter wheat yields.

It should be noted that under controlled drought when the polymer gel was applied to a depth of 20-22 cm, and in field experiments under sufficiently favorable moistening conditions, productive tillering, grain weight per ear, and 1000-grain weight most closely correlated with yield.

So, under the conditions of simulated soil drought, the domestic hydrogels Ritina-10 and V-415 K when placed at a depth of 20-22 cm have a statistically significant effect ($p < 0.001$ and $p < 0.01$, respectively) on the yield value (an increase by 25.0-27.7%) and yield components of grain crops. For Ritin-10, the yield values correlated inversely with the number of productive stems ($r = -0.83$), the number of grains per ear ($r = -0.78$) and the grain weight per ear ($r = -0.78$), for V-415 K hydrogel, with productive tillering ($r = 0.70$), the grain weight per ear ($r = 0.74$) and the 1000-grain weight ($r = 0.71$). The hydrogel introduced into the root-inhabited soil layer (10-12 cm) dried up without irrigation and did not act as a water-retaining soil additive. Under field conditions, the Aquasorb hydrogel (20 kg/ha) + N_{45} ($p < 0.05$) and Aquasorb (40 kg/ha) + N_{45} ($p < 0.01$) increased the yield of wheat. In the semi-arid period, with Aquasorb 20 kg/ha, the yield had a close inverse correlation with the weight of grain per ear ($r = -0.99$) and the 1000-grain weight ($r = -0.98$). For Aquasorb 40 kg/ha, the yield showed a close inverse correlations with the grain number per ear ($r = -0.99$) and the grain weight per ear ($r = -0.87$). Grain yield also closely correlates with the number of grains per ear ($r = -0.83$) when Aquasorb (20 kg/ha and 40 kg/ha) was applied together with nitrogen fertilizers. In wet and moderately wet years, a strong dependence occurred of yield on the crop structure parameters occurred ($r = 0.84$-0.99). Therefore, in the field trials during a dry growing season, it is necessary to apply a high dose of hydrogel (40 kg/ha) in combination with nitrogen fertilizers. In moist and moderately humid growing seasons, a dose of 20 kg/ha is sufficient when using with nitrogen fertilization.

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