Comparative assessment of the genotypes of oats of domestic and foreign breeding to the toxic effect of aluminum ions

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Abstract. The purpose of the research is to identify the genetic resistance to the toxic effects of aluminum ions in oat genotypes for the targeted selection of aluminum-resistant varieties. The work was carried out on the basis of the laboratory of genomic research in crop production of the Research Institute of Agricultural Sciences, a branch of the Tyumen Scientific Research Center SB RAS in 2024. The research object were oat species: *Avena sativa L.*, *A. abyssinica L.*, *A. strigosa L., A. byzantina L.* The research is based on changes in the growth of plant roots during the phase of early ontogenesis (the first 7 days) under the action of aluminum ions. Aqueous solutions of aluminum sulfate were prepared at a concentration of 1.5; 3.0; 5.0 g/l with concomitant measurement of the acidity level (pH). Distilled water was used as a control. The most resistant to the toxic manifestation of aluminum ions at concentrations of 1.5 and 3.0 g/l in solution was the Tobolyak variety (k-15827), which belongs to the species *Avena sativa L.* The root length index was 57 and 20%, respectively (root length 89±1.8 and 32±0.9 mm). Aluminum-resistance in the variant with a maximum concentration (5.0 g/l) of Al^{3+} in solution is noted in oat genotypes Raduzhny (*A. sativa L.,* k-15887) and Mestny (*A. strigosa L.,* k-5200) root length index reached 10% relative to the control. The oat genotypes belonging to the species *Avena abyssinica L.* were unstable to the effects of aluminum ions. (Mestny k-4971 and k-5075). At an aluminum ion concentration of 3.0 g/l, the genotype of *Avena byzantina L.* (Haruabusa k-14873) was the least resistant to stress – the root length index was 11% relative to the control. The mathematical dependence of the root length of oat sprouts correlated (R^2=1) with the concentration of Al^{3+} in solution was also determined, expressed by the following regression equation: $y=5{,}32x^2-48{,}4x+117{,}34$ where y is the index of the root length of seven-day oat seedlings, mm; x is the concentration of aluminum ions, g/l.

1 Introduction

Aluminum is ubiquitous in the Earth's crust and occurs as insoluble deposits and is biologically inactive [1]. As a result of anthropogenic stress, soil acidification and

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aluminum mobilization occur. Due to its widespread use, this metal has a direct effect on the vital activity of organisms [2]. In the composition of acidic soils according to E.L. Klimashevsky, aluminum contains from 270 to 2700 mg/l of soil solution [3]. The high content of mobile aluminum in sod-podzolic and gray-forest soils is due to the soil formation process and is the most important cause of its acidification [4].

In the Russian Federation, the territory of acidic soils reaches 40% of the acreage [5]. Aluminuim-toxicity is manifested by aberration in root cells, affecting biological and physiological processes, which leads to a deficiency in the supply of nutrients to plants, affecting productivity [6, 7]. In the work of J.F. Ma it was noted that aluminum ions disrupt the structure and functions of the plant cell wall, as well as the plasma membrane, by binding several cellular sites [8]. As a result of evolution, plants have developed a mechanism for the external detoxification of Al^{3+} by releasing anions of organic acids from the root, alkalizing the rhizosphere [9].

Oat is a cereal crop that is widely distributed in the feed and food sector around the world [10]. This culture has a relative plasticity to edaphic stress [11]. At the same time, for favorable growth and development of oat plants, the reaction of the medium (pH) should vary from 5.0 to 7.7 units [12]. Oat (*Avena L.*) includes weed-field, wild, and cultivated species that have valuable characteristics and properties, being an important source for breeding [13-15]. In this regard, to promote targeted breeding, methods of searching for genotypes of oat plants resistant to aluminum ions among wild species are relevant.

The purpose of the research is to identify the genetic resistance to the toxic effects of aluminum ions in oat genotypes for the targeted selection of aluminum-resistant varieties.

2 Materials and Methods

The work was carried out on the basis of the laboratory of genomic research in crop production of the Research Institute of Agricultural Sciences, a branch of the Tyumen Scientific Research Center SB RAS in 2024. The research object were 8 oat genotypes of various species (*Avena sativa L.*, *A. abyssinica L.*, *A. strigosa L., A. byzantina L.*), which are achievements of domestic and foreign breeding (Table 1).

Table 1. List of oat genotypes used in the experiment to study the effect of aluminum ions in the early ontogenesis stages.

No.	VIR catalog number	Name	Species	Origin
1	15827	Tobolyak	*Avena sativa L.*	Russia (Tyumen region)
2	15887	Raduzhny	*A. sativa L.*	Russia (Tyumen region)
3	5075	Mestny	*A. abyssinica L.*	Ethiopia
4	4971	Mestny	*A. abyssinica L.*	Ethiopia
5	4483	Mestny	*A. strigosa L.*	UK
6	5200	Mestny	*A. strigosa L.*	Spain
7	14471	Alden Penas	*A. byzantina L.*	Spain
8	14873	Haruabusa	*A. byzantina L.*	Japan

The research is based on the ability of oat seeds to respond adequately to aluminum ions by changing the growth of plant roots in the first 7 days of life. Aqueous solutions of aluminum sulfate were prepared at a concentration of 1.5; 3.0; 5.0 g/l with concomitant measurement of the acidity level (pH). Distilled water was used as a control. Germination samples were laid by the roll method of 25 grains in fourfold repetition (GOST 12038-84). To create the necessary conditions for grain germination, the prototypes were placed in an electric dry-air thermostat TS-1/80 SPU and germinated at a temperature of 21°C. After 7 days, laboratory germination was determined, and the seedlings were measured: the length of the largest root; the air-dry mass of the roots of experimental and control samples. The root length index (RLI) was determined by the ratio of the average root length of control and experimental plants. Mathematical data processing and analysis of variance were performed using the AgCStat add-in for the Microsoft Excel software product [16].

3 Results and Discussion

During the research, it was found that the laboratory germination of various oat genotypes in the control varied from 78±0.9 to 95±0.5% (Table 2). The acidity level (pH) of the aqueous solution at the control was 6.0 units. (Fig. 1). Germination of oat genotypes k-5075 (Mestny) and k-14873 (Haruabusa) at a concentration of aluminum ions in a solution of 1.5 g/l had a positive effect on grain germination reaching 93±0.4 and 84±0.4%, respectively, which is 9 and 6% higher than the control values. This may be due to protective mechanisms that protect oat seedlings from toxic effects in the juvenile period [17]. At the same time, the acidity level of an aqueous solution with a concentration of Al^{3+} 1.5 g/l increased by 32% relative to the control, which corresponded to a pH of 4.1. Aluminum ions at a concentration of 1.5 g/l had no negative effect on the germination of the variety (k-15887) – the deviations were within the experimental error (79±1.0). In the variant with a concentration of Al^{3+} of 1.5 g/l, a decrease in laboratory germination of grain by 2-6% was noted relative to the control of the following oat genotypes: k-15827, k-4971, k-4483, k-5200, k-14471 reaching 76-93%.

Table 2. Laboratory germination of oat genotypes on the seventh day, depending on concentrations of aluminum ions in solution ($X_{av.}$±SE), %.

Variety name (VIR catalog number)	Concentration of Al^{3+}, g/l			
	Control	1.5	3.0	5.0
Tobolyak (k-15827)	86±1.0	81±1.0	83±0.8	75±1.0
Raduzhny (k-15887)	80±0.6	79±1.0	63±0.5	62±0.7
Mestny (k-5075)	84±0.4	93±0.4	83±1.0	72±0.5
Mestny (k-4971)	93±0.7	91±0.5	93±1.0	79±1.3
Mestny (k-4483)	82±1.1	76±1.0	49±1.5	34±1.7
Mestny (k-5200)	95±0.5	93±1.2	79±0.8	74±0.5
Alden Penas (k-14471)	85±0.4	81±1.1	77±0.7	59±0.7
Haruabusa (k-14873)	78±0.9	84±0.4	75±0.7	81±0.8
Average value	85	85	75	67
$X_{av.}$ – average value of laboratory germination, %; SE – standard error, %.				

An increase in the concentration of aluminum ions in solution to 3.0 g/l led to an increase in the laboratory germination of the oat genotypes k-15827 (Tobolyak) and k-4971 (Mestny) by 2%, relative to the previous variant (1.5 g/l), reaching 83±0.8 and 93±1.0%, respectively. In the work of Batalova G.A., it was noted that low concentrations of aluminum ions can have a positive effect on plant growth [18]. This is due to the release of organic acids from the protoplasts of plant root cells, which minimize the toxic effect of aluminum ions, as described in the works of many authors [19, 20]. The rest of the studied oat samples were less resistant to the toxic effects of Al^{3+} – grain germination decreased by 4-27% relative to the variant with a concentration of aluminum ions in a solution of 1.5 g/l. An increase in the concentration of Al^{3+} in the solution provided an increase in acidity from 6.0 (control) to 3.9 units.

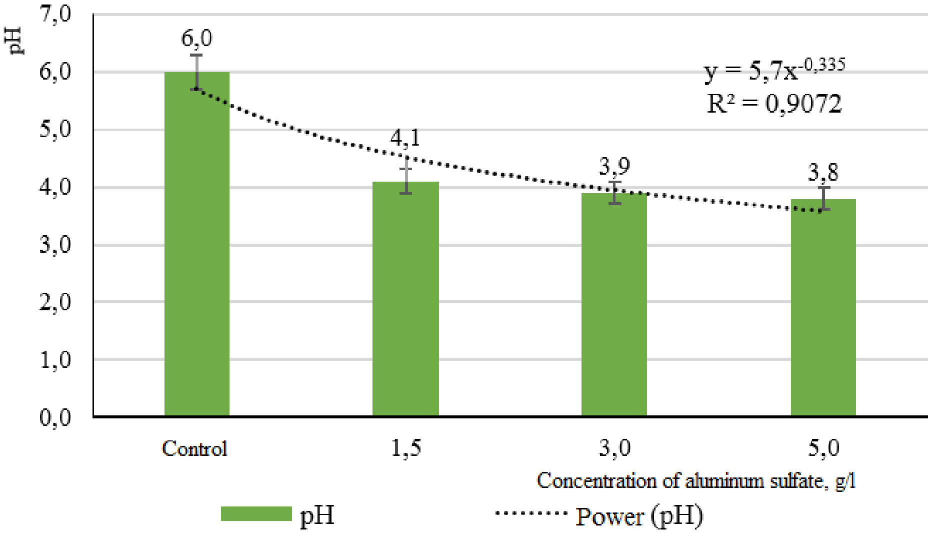

Fig. 1. The effect of different concentrations of aluminum sulfate on the reaction of the medium (pH) of an aqueous solution at a 5% error level, units.

In the variant with the maximum concentration of Al^{3+} in solution, there was an increase in the laboratory germination index in the variety Haruabusa (*A. byzantina L.*) k-14873 by 6%, relative to the previous variant (3.0 g/l), reaching 81±0.8%. Aluminum ions had no significant effect on germination in the Raduzhny oat variety (*A. sativa L.*) k-15887, deviations were within the experimental error (62±0.7%). The rest of the studied oat genotypes were less resistant to stress, which led to a decrease in grain germination (79-34%).

During the research, a high mathematical relationship was established between the concentration of aluminum ions and the reaction of the solution medium (pH). The regression power equation is valid in the range of aluminum ion content in the substrate up to 5.0 g/l. The equation corresponds to the following type: $y=5,7x^{-0,335}$where y is the reaction of solution medium (pH), units; x is the concentration of Al^{3+} in solution, g/l. The coefficient of determination (R^2) was 0.91.

Starting from the early stages of ontogenesis, under the influence of toxic aluminum ions, plants experience stress, which as a result affects the root system development. It was found that the average root length of seven-day-old oat seedlings in the control reached from 117±0.9 mm to 188±1.9 mm (Table 3). Due to the oat species, the weight of the roots of seedlings in the control was significantly different and varied from 0.09 to 0.41 g (Table 4). In the species *Avena strigosa L.* the weight of the roots in the control was 0.09-0.14 g. Whereas on the rest of the samples, this indicator exceeded by more than 2 times. Regardless of the studied oat genotypes, a 1.8-2.5-fold decrease in root length relative to the control was recorded in the variant with a concentration of Al^{3+} 1.5 g/l. At the same time, the toxicity of aluminum ions had a slight decrease in root weight relative to the control, reaching 0.08-0.41 g. The most resistant to the stress effects of Al^{3+} at a concentration of 1.5 g/l was the Tobolyak variety (k-15827) – the root length index at a 5% error level was 57% (Fig. 2).

Table 3. The average root length of seven-day oat seedlings, depending on the concentration of aluminum ions ($X_{av.}$± SE), mm.

Species	VIR catalog number	Concentration of Al^{3+}, g/l			
		Control	1.5	3.0	5.0
Avena sativa L.	15827	157±0.7	89±1.8	32±0.9	13±0.1
	15887	116±0.9	53±0.7	22±0.5	12±0.3
Avena abyssinica L.	5075	143±0.8	58±1.9	19±0.3	10±0.1
	4971	188±1.9	78±0.7	23±0.5	12±0.1
Avena strigosa L.	4483	117±0.9	60±0.6	22±0.04	11±0.3
	5200	136±1.1	58±0.2	19±0.2	14±0.4
Avena byzantina L.	14471	170±1.2	91±0.9	29±0.5	12±0.2
	14873	161±0.9	81±0.3	18±0.2	12±0.1
Group average		149	71	23	12
$X_{av.}$ – average length, mm; SE – standard error, mm.					

An increase in the concentration of aluminum ions in solution to 3.0 g/l led to a decrease in the length of the primary roots of oat seedlings by 4.9-8.9 times relative to the control, reaching 18-32 mm. There is also a regular decrease in the root weight of seven-day oat seedlings from 1.8 (Tobolyak k-15827) to 2.9 (Mestny k-5075 and k-4971) times relative to the initial values. This is explained by the toxic effect of aluminum ions on plants, causing chromosomal mutations in the cells of the apical meristem of the root, which subsequently limits the absorption of water and nutrients [21-23]. At the same time, the maximum values of the root length index in the variant with a concentration of Al^{3+} 3.0 g/l were observed in the Tobolyak variety (k-15827) – 20%.

Table 4. The air-dry mass of the roots of seven-day-old oat seedlings, depending on the concentration of aluminum ions in solution, g.

Species	VIR catalog number *(factor A)*	Concentration of Al^{3+}, g/l *(factor B)*			
		Control	1.5	3.0	5.0
Avena sativa L.	15827	0.41	0.41	0.23	0.08
	15887	0.31	0.28	0.14	0.07
Avena abyssinica L.	5075	0.26	0.25	0.09	0.03
	4971	0.40	0.31	0.14	0.03
Avena strigosa L.	4483	0.09	0.08	0.04	0.01
	5200	0.14	0.13	0.06	0.03
Avena byzantina L.	14471	0.40	0.36	0.19	0.05
	14873	0.37	0.37	0.16	0.09
LSD_{05} by factor A=0.02; LSD_{05} by factor B=0.01; LSD_{05} by interaction AB=0.02					

At a high concentration of aluminum ions (5.0 g/l), the greatest root length of seven-day oat seedlings was in the k–5200 (Mestny) genotype, which belongs to the species *A. strigosa* - 14±0.4 mm. Whereas the rest of the samples had a root length of 10-13 mm, which is more than 10 times less than the control values. Such high concentrations of aluminum ions in the solution also negatively affected the weight of the roots of oat seedlings, which reached minimum values (0.01-0.09 g). The most resistant to stress at a concentration of Al^{3+} 5.0 g/l were the genotypes of oats k-15887 (Raduzhny) and k-5200 (Mestny) – the root length index was 10%.

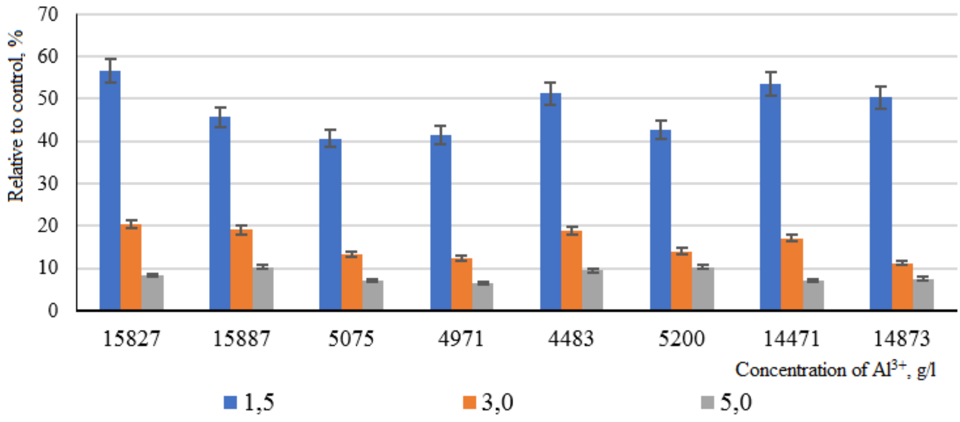

Fig. 2. The root length index of seven-day oat seedlings depending on the concentration of aluminum ions at a 5% error level, %.

Based on the conducted studies, a quadratic regression equation was calculated showing the relationship between the manifestation of aluminum-toxicity and the development of the root system of plants. The regression equation is as follows (reliable in the range of Al^{3+} content in solution up to 5.0 g/l): $y=5{,}32x^2-48{,}4x+117{,}34$ where y is the root length index of seven-day oat seedlings, mm; x is the concentration of aluminum ions, g/l. The determination index (R^2) is equal to 1, which corresponds to the ideal model of the regression line, proving the dependence of the index of the oat root length of the Tobolyak variety (k-15827) with the concentration of Al^{3+} in solution.

4 Conclusions

The most resistant to toxic manifestation of aluminum ions with concentrations of 1.5 and 3.0 g/l in solution was the oat genotype of Tobolyak (k-15827), which belongs to the *Avena sativa L.* species – accordingly, the root length index was 57 and 20% relative to the control. Aluminum-resistance in the variant with a maximum concentration (5.0 g/l) of Al^{3+} in solution is noted in oat genotypes Raduzhny (*A. sativa L.,* k-15887) and Mestny (*A. strigosa L.,* k-5200) root length index reached 10% relative to the control. The oat genotypes belonging to the species *Avena abyssinica L.* were unstable to the effects of aluminum ions. (Mestny k-4971 and k-5075). At a concentration of Al^{3+} in a solution of 3.0 g/l, the oat genotype k-14873 (*A. byzantina L.,* Haruabusa) was the least resistant to stress – the root length index was 11% relative to the control.

The mathematical dependence of the root length of oat sprouts correlated (R^2=1) with the concentration of Al^{3+} in solution was determined, expressed by the following regression equation: $y=5{,}32x^2-48{,}4x+117{,}34$ where y is the index of the root length of seven–day oat seedlings, mm; x is the concentration of aluminum ions, g/l.

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