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PLANT GROWING

Innovational Trends in Apple Breeding and Fruit Quality

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Abstract—The innovational trends in apple breeding include the development of triploid scab immune apple cultivars. The long-term phytopathological and biological studies made it possible to develop approximately 20 first home scab immune apple cultivars and include them in the State Register of Breeding Successes. For the first time in Russia and in the world, the biological and cytoembryological studies favored the development of a number of triploid cultivars that are characterized by high marketability and better biochemical composition of fruit in comparison with well-known old cultivars and diploid scab nonimmune cultivars of VNIISPK breeding.

Keywords: apple, breeding, cultivar investigation, immunity to scab, polyploidy, combining of scab immunity and triploidy

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The All-Russia Research Institute of Breeding of Fruit Crops (VNIISPK) is the oldest pomological and breeding institute in Russia (over 170 years old); studies are carried out there in the breeding orchards and gardens as well as in the laboratory of biochemical and technological evaluation of cultivars and storage by conventional methods [1–6].

Development of scab immune triploid cultivars of apple trees is a priority in breeding. Scab (*Venturia inaequalis* (Cke) Wint.) is one of the most harmful diseases for this culture. I.V. Michurin [7] and N.I. Vavilov [8] considered breeding as the most radical way to defeat diseases. Priority in the development of scab immune apple cultivars is owned by American scientists [9].

Deliberate large-scale program on breeding for the immunity to scab has been conducted in VNIISPK since 1976. From 1977 to 2015, 2320 mating combinations were carried out, 2.4 million flowers were pollinated, 1 million hybrid seeds were received, 60500 seedlings were grown, and 23 scab immune cultivars were created and zoned. Homologated assortment of apple got four cultivars only in the last 3 years (2013–2015): Alexander Boyko (2013), Priokskoe (2014), Vavilov (2015), and Poeziya (2015).

In Russia, scab immune apple cultivars were developed for the first time in VNIISPK, and the first domestic immune cultivar Imrus (immune Russian) was developed and zoned in 1996. In addition to the practical work, V.V. Zhdanov developed the genetic and immunological basis for the breeding of scab immune cultivars in the institute. The methods for artificial scab infection have been improved [10], the most virulent and aggressive biotypes were chosen for the artificial infectious background, the programs for crossings were developed, genotypic structure for used donors on the basis of immunity was refined, and scientific recommendations for the intensification and acceleration of breeding of disease immune apple cultivars on a new genetic basis were developed. After that, scientists and other institutions joined this work. Great achievements in this direction were obtained at the Institute of Genetics and Selection of Fruit Plants [11].

Table 1 shows comparative data on the quality of fruit of diploid scab nonimmune cultivars bred in VNIISPK and control widespread diploid cultivars Papirovka, Melba, Osennee Polosatoe, Antonovka Obyknovennaya, and Severnyi Sinap. All 19 apple cultivars are practically as good as control grades and exceed them by weight, appearance, and amount of sugars. This trend continues in the comparison of scab immune cultivars bred in VNIISPK with control cultivars (Table 2).

Another innovative direction in the breeding of apples in VNIISPK is the development of triploid cultivars. They are characterized by early appearance of fruit, productivity, more regular fruiting, increased self-fertilization, resistance to scab, and high marketability of fruits. The history of apple breeding on the polyploid level is the following. In the late 1930s–early 1940s, Swedish researchers found that spontaneously developed triploid cultivars favorably differ from diploid ones in a number of economically valuable features. The breeding of triploid cultivars is of great interest, and the development of this area opens a new

Table 1. Fruit quality of diploid nonimmune cultivars of apple bred in VNIISPK (an average for a number of years)

Cultivar	Ripening time	Fruit weight, g	Appearance/ taste, points	Indicator of the biochemical composition of fruits				
				sum of sugars, %	titratable acidity, %	ascorbic acid, mg/100 g	P-active substances, mg/100 g	sugar acid ratio
Veteran	W	130	4.4/4.4	10.3	0.71	19.4	229	14.5
Zhelannoe	S	130	4.6/4.4	10.6	0.61	4.4	384	17.4
Zaryanka	F	130	4.3/4.3	10.1	0.79	18.0	419	12.8
Kulikovskoe	W	125	4.4/4.2	10.2	0.53	15.3	317	19.2
Morozovskoe	W	160	4.6/4.3	8.7	1.04	8.0	299	8.4
Olimpiyskoe	W	130	4.3/4.2	10.9	0.77	15.4	280	14.2
Orlik	W	120	4.4/4.5	10.8	0.43	8.5	222	25.1
Orlinka	S	140	4.3/4.3	10.4	0.73	7.4	314	14.2
Orlovim	S	130	4.4/4.5	10.2	0.77	8.8	299	13.2
Orlovskaya Zarya	W	135	4.6/4.5	10.3	0.63	15.0	334	16.3
Orlovskiy Pioner	F	140	4.3/4.3	10.0	0.87	14.8	514	11.5
Orlovskoe Polosatoe	F	150	4.6/4.3	10.3	0.81	8.5	261	12.7
Pamyat Voinu	W	140	4.4/4.5	10.6	0.51	7.1	182	20.8
Pamyat Isaevu	W	150	4.5/4.3	10.4	0.56	6.6	325	18.6
Pepin Orlovskiy	W	140	4.5/4.2	10.2	0.59	15.3	241	17.3
Radost Nadezhdy	S	150	4.4/4.3	10.7	0.64	4.7	474	16.7
Rannee Aloe	S	130	4.5/4.4	9.5	0.78	11.6	298	12.2
Sinap Orlovskiy	W	150	4.4/4.4	9.9	0.56	13.4	205	17.7
Slavyanin	W	150	4.5/4.3	10.5	0.93	11.4	360	11.3
$\bar{x} \pm S_{\bar{x}}$		138 ± 2	4.4 ± 0.02/4.3 ± 0.02	10.2 ± 0.1	0.70 ± 0.04	11.2 ± 1.0	314 ± 20	15.5 ± 0.9
V, %		7.8	2.4/2.3	4.9	22.4	40.3	28.0	25.3
Control widespread diploid cultivars								
Papirovka	S	125	4.3/4.2	9.1	0.75	15.1	259	12.1
Melba	S	130	4.3/4.4	9.9	0.71	11.2	389	13.9
Osennee Polosatoe	F	130	4.5/4.4	9.8	0.59	9.0	248	16.6
Antonovka Obyknovennaya	W	140	4.3/4.2	8.7	0.99	14.5	340	8.8
Severnyi Sinap	W	120	4.3/4.2	9.0	0.58	13.9	259	15.5
$\bar{x} \pm S_{\bar{x}}$		129 ± 3	4.3 ± 0.04/4.3 ± 0.05	9.3 ± 0.2	0.72 ± 0.07	12.7 ± 1.1	299 ± 28	13.4 ± 1.4
V, %		5.7	2.1/2.6	5.6	22.9	20.2	20.8	23.0

Table 2. Fruit quality of zoned scab immune apple cultivars bred at VNIISPK (average for a number of years)

Cultivar	Ripening time	Fruit weight, g	Appearance/ taste, points	Indicator of the biochemical composition of fruits				
				sum of sugars, %	titratable acidity, %	ascorbic acid, mg/100 g	P-active substances, mg/100 g	sugar acid ratio
Afrodita	W	125	4.4/4.4	10.6	0.46	6.3	374	23.0
Bolotovskoe	W	150	4.3/4.4	10.6	0.40	10.6	497	26.5
Venyaminovskoe	W	130	4.4/4.4	10.5	0.63	4.5	254	16.7
Zdorovye	W	140	4.5/4.3	9.7	0.85	7.6	428	11.4
Ivanovskoe	W	150	4.4/4.4	11.8	0.85	18.3	352	13.9
Imrus	W	140	4.3/4.4	9.7	0.75	7.6	388	12.9
Kandil Orlovskiy	W	120	4.4/4.3	10.7	0.41	5.4	463	26.1
Kurnakovskoe	W	130	4.3/4.3	10.9	0.68	8.7	328	16.0
Orlovskoe Polesye	W	140	4.4/4.3	10.3	0.80	6.6	396	12.9
Pamyati Khitrovo	W	170	4.3/4.3	10.6	0.84	3.2	429	12.6
Poeziya	W	140	4.4/4.3	10.4	0.86	2.7	234	12.1
Priokskoe	W	150	4.5/4.4	12.6	0.63	4.3	333	20.0
Svezhest	late F.	140	4.3/4.3	10.1	0.80	12.5	377	12.6
Solnyshko	F	140	4.4/4.3	9.8	0.84	7.7	424	11.7
Start	W	140	4.3/4.3	10.9	0.57	11.0	404	19.1
Stroevskoe	W	120	4.5/4.4	10.4	0.61	7.0	396	17.0
Yubiley Moskvy	W	120	4.3/4.3	9.9	0.69	5.9	349	14.3
$\bar{x} \pm S_{\bar{x}}$		138 ± 16	4.4 ± 0.01/ 4.3 ± 0.05	10.6 ± 0.2	0.69 ± 0.04	7.6 ± 0.9	378 ± 16	16.4 ± 1.2
V, %		9.5	1.7/1.2	7.0	22.9	50.1	17.8	30.1

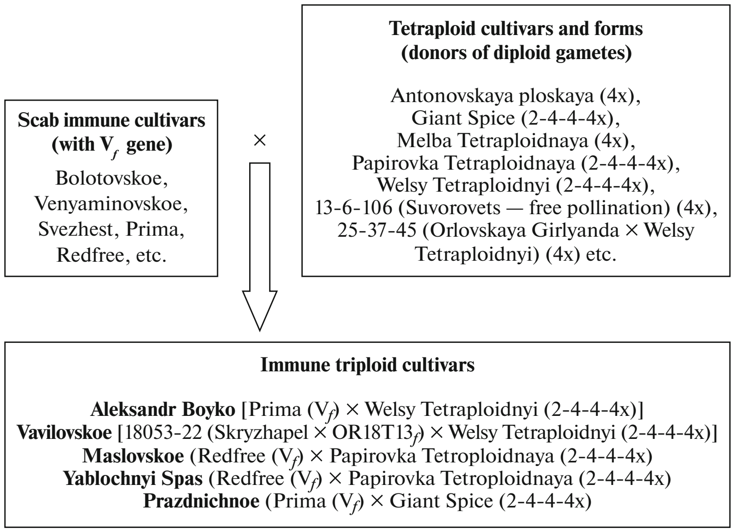
era of apple breeding [12]. Unfortunately, such studies have not received any development for an inexplicably long time.

The breeding of apple trees on the polyploid level has been carried out in VNIISPK since 1970. Over 46 years (1970–2015), 455 combinations of crosses was carried in this area of breeding, 47 900 of hybrid seedlings were grown, 20 triploid cultivars, including intervalence crosses from 16 cultivars, were developed; ten of them are already included in the State Register of Breeding Successes (zoned) [13, 14].

Cytoembryological control was carried out on the polyploid level during the breeding of apple: the ploidy of a hybrid offspring derived from heteroploid crosses was determined, the state of generative structures was studied—meiosis at microsporogenesis and the formation of male gametophyte, megasporogenesis and the formation of female gametophyte. These data made it possible to correctly select the original forms for crossing and to predict, to some extent, the outcome of such crosses. Crosses of orthoploid forms of diploid × tetraploid and tetraploid × diploid types were found to be the most effective to create hybrid triploids.

To date, the ploidy of more than 14000 seedlings from the crosses of diploid × tetraploid type and more than 1500 seedlings from the crosses of tetraploid × diploid type were determined. The average amount of triploid plants in 2x × 4x combinations is 68%, and is 54% in 4x × 2x combinations; the amount of tetraploid plants is 0.17 and 23.44%, respectively. This difference is explained by high self-fertilization of individual tetraploid forms, in which "its own" diploid pollen is preferably involved in the fertilization.

Meiosis during the microsporogenesis was studied in a number of periclinal chimeras of type I: Antonovka Ploskaya (2-4-4-4x), Welsy F (2-4-4-4x) Welsy-M (2-4-4-4x), Papirovka (2-4-4-4x), Giant Spice (2-4-4-4x); homogeneous tetraploids: McIntosh (4x), 13-6-106 form (4x); and homogeneous tetraploid forms isolated during the breeding on the polyploid level: 25-35-120 (4x), 25-35-121 (4x), 25-35-144 (4x),



Scheme for the development of triploid apple cultivars.

25-37-35 (4x), 25-37-33 (4x), 25 37-45 (4x), and 30-47-88 (4x).

Triploid cultivars of apple bred in VNIISPK (Table 3) greatly exceed both nonimmune diploid (Table 1) and immune diploid (Table 2) cultivars by the weight, the appearance of fruits, and the content of P-active substances, but they are inferior to them in the content of ascorbic acid in the fruit.

The development of immune triploid cultivars is of particular interest. To date, eight scab immune (V_f gene) and triploid cultivars of apple were developed. Six of those triploid cultivars were derived from the heteroploid crosses of 2x × 4x type, in which one parent was the donor of the immunity to scab (V_f gene), and the second one was the donor of diploid gametes (tetraploid). The concept of development of scab immune triploid apple cultivars is shown in the figure. Triploid scab immune cultivars can be received from the crosses of this type.

In some cases, it is possible to develop scab immune triploid cultivars from two diploids, if one parent has the immunity gene (e.g., V_f genome), and

Table 3. Fruit quality of triploid apple cultivars bred at VNIISPK (average for a number of years)

Cultivar	Ripening time	Fruit weight, g	Appearance/ taste, points	Indicator of the biochemical composition of fruits				
				sum of sugars, %	titratable acidity, %	ascorbic acid, mg/100 g	P-active substances, mg/100 g	sugar acid ratio
Avgusta	S	160	4.4/4.4	10.8	0.73	9.8	472	14.8
Bezhin Lug	W	150	4.4/4.3	9.3	0.55	7.4	435	16.8
Blagodat	W	200	4.4/4.4	13.6	0.73	5.8	345	18.6
Daryona	S	170	4.5/4.4	10.3	0.76	8.8	422	13.5
Zhilinskoe	W	190	4.4/4.4	10.6	0.56	5.8	376	18.9
Ministr Kiselev	W	170	4.4/4.4	11.9	0.45	7.8	383	26.5
Orlovskiy Partizan	W	200	4.5/4.4	11.8	0.41	7.7	427	28.8
Osipovskoe	S	130	4.4/4.4	12.2	0.60	9.2	263	20.3
Patriot	W	240	4.5/4.3	11.9	0.46	9.0	449	25.8
Turgenevskoe	W	180	4.4/4.3	12.4	0.53	4.6	447	23.4
Pamyat Semakinu	W	160	4.5/4.2	9.4	0.77	11.5	388	12.2
$\bar{x} \pm S_{\bar{x}}$		177 ± 9	4.4 ± 0.02/ 4.4 ± 0.02	11.3 ± 0.4	0.59 ± 0.04	7.9 ± 0.6	401 ± 18	20.0 ± 1.7
V, %		16.8	1.1/1.6	11.8	22.2	25.3	14.8	27.8

Table 4. Fruit quality of triploid scab immune apple cultivars bred at VNIISPK (average for a number of years)

Cultivar	Ripening time	Fruit weight, g	Appearance/ taste, points	Indicator of the biochemical composition of fruits				
				sum of sugars, %	titratable acidity, %	ascorbic acid, mg/100 g	P-active substances, mg/100 g	sugar acid ratio
Triploid cultivars from intervalence crosses								
Aleksandr Boyko	W	200	4.4/4.3	10.7	0.51	4.4	351	21.1
Vavilovskoe	W	170	4.6/4.3	13.0	0.67	5.1	337	19.4
Maslovskoe	S	230	4.3/4.3	10.7	0.71	17.5	318	15.1
Spasskoe	S	170	4.4/4.4	11.6	0.60	12.4	366	19.4
Yablochnyi Spas	S	210	4.4/4.3	10.6	0.64	9.4	402	16.5
Triploid cultivars from diploid crosses								
Rozhdestvenskoe	W	140	4.4/4.3	10.0	0.58	4.1	366	17.3
Yubilyar	S	130	4.4/4.2	9.4	0.86	11.5	388	11.0
$\bar{x} \pm S_{\bar{x}}$		179 ± 16	4.4 ± 0.03/ 4.3 ± 0.02	10.9 ± 0.4	0.65 ± 0.04	9.2 ± 1.9	361 ± 11	17.1 ± 1.3
V, %		9.5	2.0/1.3	10.7	17.1	54.4	8.0	19.7

one of the parents is prone to the formation of unreduced gametes. The examples are two developed scab immune triploid cultivars—Rozhdestvenskoe [Welsy × VM 41497 (V_f)] and Yubilyar [814 (V_f), free pollination]—that were included in the State Register of Breeding Successes.

According to our research data, hybridization at the polyploid level yielded 2.3 times lower the amount of seeds and 4.7 times lower the amount of grown one-year-old seedlings relative to the pollinated flowers than hybridization performed at the diploid level. However, the selective value of the seedlings obtained by hybridization at the polyploid level was significantly higher, as was evidenced by the following data. Hybridizing at the diploid level, an average amount of 4121 seedlings are needed to be grown to identify one elite seedling, while only 778 are needed at the polyploid level; an average amount of 86600 flowers were pollinated and 16700 year-old seedlings were grown to create one Cultivar that is transferred to the state test at the diploid level, while only 46200 and 2900, respectively, at the polyploid level (almost six times less).

It was shown that triploid immune cultivars derived from both intervalence crosses and diploid cultivars are significantly superior to control widespread diploid cultivars by the weight, appearance, and content of P-active substances in the fruits, but they are inferior to them in the content of ascorbic acid (Table 4).

Thus, approximately 20 diploid cultivars and first scab immune domestic (over 20) cultivars were developed at VNIISPK. A series of triploid cultivars from intervalence crosses was developed for the first time in Russia and the whole world. The scheme for the creation of scab immune triploid cultivars was developed. The first scab immune triploid cultivars were created that were not inferior to the widespread cultivars of apple but that surpass them in a number of indicators of merchantability and consumer qualities of fruits.

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