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Physical and mechanical properties of berries and biological features of red currant growth for mechanized harvesting

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Abstract: The physical and mechanical parameters of berries and the morphometric features of the structure of the bush growth habit are important criteria in predicting the use of berry harvesting equipment. In this research, six red currant cultivars have been studied. The berry separation force, the crushing force, and the strength of attachment of the berries to the stalk were assigned to the physical and mechanical parameters and were determined using the "PLODTEST-1" and "Dina-2" devices (Russia). For the optimal operation of the berry harvester, the crushing force of the berries must be more than 2 N, the berry separation force must be in the range of 0.5–1.5 N. A high correlation between the separation and crushing forces was determined (R = 0.71). During the period of technical maturity, the strength of the attachment of the berries in the raceme was more than 0.5 N and, by the end of maturation, this indicator decreased. Most of the studied cultivars have a compact, optimal bush volume. The red currant cultivars Niva, Asya and Vika are promising for mechanised harvesting.

Keywords: cultivar; berry separation force; force of crushing; ratio of berry strength; bush growth habit

Berry crops play an important role in solving the problems of rational and the healthy nutrition of the world's population. Among the berries, a special place belongs to red currants, as a valuable source of vitamins A, C, E, trace elements Mg, Fe, K, pectin substances and B-carotene. Today, berry picking is one of the most time-consuming, tedious and economically costly operations. Up to 60–70% of all production costs are accounted for with the manual harvesting, so there is a fairly clear trend to intensify the development of red currant cultivars suitable for mechanised harvesting (Huffman 2012; Aliasgarian et al. 2013; Panfilova, Golyaeva 2017; Orchard et al. 2019). The design of berry harvesters makes it possible to significantly increase the profitability of a berry crop production, i.e., to reduce the manual labour costs by 10–15 times, and to reduce the direct operating costs. The efficiency of using harvesters largely depends on the selection of the assortment with certain bush parameters, the physical and mechanical properties of the berries and a complex of economically valuable features (Tahvonen 1979; Dale et al. 2010). For the first time, berry harvesters have been used on black currants, rose hips, raspberries, the sea buckthorn, and only then on red currants. The work of the harvester was based on shaking the shoots with a certain vibration frequency. Special attention was paid to the flexibility of the branches, the growth habit of the bush, the timing and quality of berry maturation, and the resistance to diseases (Neumann, Sorg 1977; Dale et al. 1994; Hummer and Barney 2002; Olander 2012; Sarig 2012; Kanarsky, Makarychev 2019). In this regard, the requirements for creating cultivars have

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changed. One of the priorities is to create new cultivars suitable for machine harvesting.

The main factors that determine the suitability of the cultivar for mechanised harvesting include the zone of the berry placement in the crown of the bush, the simultaneous maturation of the berries in the raceme and the effort to separate and crush the berries. The secondary factors include the shape of the crown, the resistance to diseases and pests, the absence of deciduous branches, the width of the base and the height of the bush, the diameter of the perennial branches, the duration of the removable maturity and the life of the plantings. Numerous studies of the physical and mechanical properties as well as the biological features of berries have been carried out on the black currant allowed one to determine the main parameters of the cultivar suitability for combine harvesting, i.e., high yield, resistance to the most common fungal diseases (*Sphaerotheca mors-uvae*), a bush of 120–160 cm in height, 140–150 cm in width, the base of the bush – not more than 30 cm, the simultaneous ripening of the berries in the raceme (90%), a separation force of the berries from the raceme within 0.5–1.5 N (50–150 g), the force of the berry crushing of more than 2 N (200 g), the duration of the removable maturity of over 7 days, and an acceptable threshold of damage to shrubs should be not more than 30% of dead branches for 6 years of exploitation (Thiele 1979; Yakimenko, Novopokrovsky 1988; Salamon 1993; Yakimenko 2001; Barney, Hummer 2005; Kikas et al. 2008). Information about the criteria for the suitability of red currant cultivars for machine harvesting is single. The purpose of this study is to determine some of the physical and mechanical properties of berries and biological features of the growth of red currant cultivars in accordance with the requirements for berry harvesting equipment and to identify promising cultivars for combine harvesting.

MATERIAL AND METHODS

The physical and mechanical properties of the berries and the biological features of the bush were studied on 6 red currant cultivars: Asya, Gazel, Vika, Niva, Osipovskaya and Jonkheer van Tets. Asya, Gazel, Vika, Niva and Osipovskaya were released at the Russian Research Institute of Fruit Crop Breeding (Russia). For comparison, the well-known Dutch cultivar Jonkheer van Tets was chosen. In 2015, the experimental plantation was planted with 2.8 × 0.5 m spacing in three-fold repetition, where there were 25 experimental plants of each cultivar in each repetition. The records were carried out in 2018–2019. For each studied cultivar, six random plants were selected for the measurements. The biological parameters, such as the height and width of the bush, the width of the base of the bush, the height of the berry placement from the soil surface were determined using a technical ruler accurate to 0.1 cm. On the basis of these measurements, the volume and compactness of the bush were calculated according to the Formulas (1–2):

$$V = H \times A \times B \tag{1}$$

$$K = \frac{H}{B} \tag{2}$$

where: V – volume of the bush (m^3); H – height of the bush (m); A – length of the bush along the row (m); B – width of the bush across the row (m); K – compactness of the bush.

The compactness of the bushes was evaluated according to five characteristics: an erected bush when the angle between the direction of the main fruit-bearing branches and the soil surface was more than 75° (ratio > 0.9); a slightly spreading bush with an angle of 60–75° (0.7–0.9); a spreading bush with an angle of 45–60° (0.6–0.7); a strongly spreading bush with an angle of 30–45° (0.4–0.6) and a trailing bush with an angle less than 30° (ratio less than 0.4). The level of the illumination of the berries was estimated in early July using a Light Meter HS 1010A luxmeter (Jinhong Electronics (HK) Ltd., China). To determine the suitability of the cultivar for the mechanised harvesting, the separation and crushing forces of the berries were determined during the period of mass maturation. The mass or simultaneous ripening of berries was determined visually when 85–90% of the yield on the bushes matured and the berries had their characteristic colour (Figure 1).

The studies were carried from 2 July to 15 July with an interval of 4 days for 10 measurements in the 3-fold repetition. One-dimensional berries in size and ripeness were selected at the rate of at least 10 pieces in one raceme. The degree of the one-dimensionality of the berries was evaluated visually. Those berries that differed slightly in size when placed along the en-

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Figure 1. Mass (simultaneous) ripening of the red currant berries (Osipovskaya)

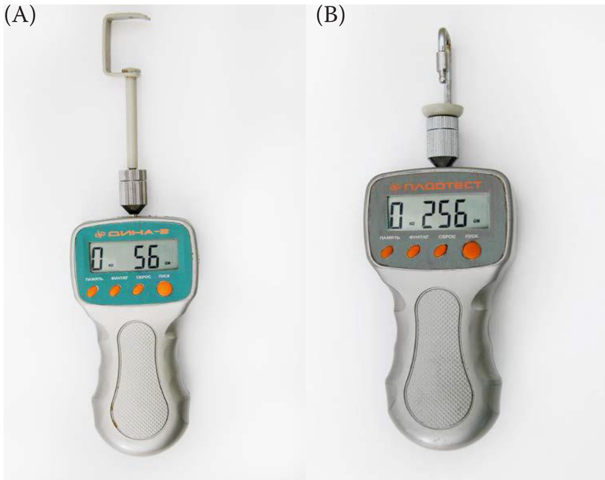

Figure 2. Power indicator (A) "Dina-2" and (B) "PLODTEST-1"

tire length of the raceme and between the racemes on the different shoots were classified as one-dimensional. The physical and mechanical properties, i.e., the force to separate the berries from the stalk were determined using the "Dina-2" device (Siberian Institute of Physics and Technology of Agrarian Problems, Russia), the range of the force determination was from 0 to 6.0 N (Figure 2A). The crushing force was measured by a "PLODTEST-1" force indicator device (Siberian Institute of Physics and Technology of Agrarian Problems, Russia), the force detection range was from 0.1 to 20.0 N (Figure 2B).

Based on the measurements, the strength limit of the berry skin was calculated using the formula of Mikhailova (2014), as the press force of the skin crushing F_p to the strength limit σ:

$$If = \frac{F_p}{S} \tag{3}$$

where: F_p – press force of crushing the skin (N); S – the cross-sectional area of the crushing plunger; in our case, the diameter of the upper pressure (plunger) was 0.9 cm.

As a comprehensive indicator of the suitability of the berries for the mechanised harvesting, the coefficient of the relative strength of the berries (k) was used:

$$k = \frac{F_p - F_0}{F_0} \tag{4}$$

where: F_0 – effort to detach the berry from the stalk (N); F_p – press force of crushing the skin (N).

According to the research of Mineyev et al. (2015) and Aleynikov and Mineyev (2016), if the relative strength coefficient of the berries (k) is ≥ 0.8, the cultivar is considered suitable for machine harvesting.

To predict the duration of the mechanised harvesting, the physical and mechanical parameters of the red currant berries were used and the following equation, based on the method of multiple linear regression (Draper, Smith 2016), was calculated:

$$Y = \sum_{i=1}^{n} B_0 + B_1 F_p - B_2 F_0 \tag{5}$$

where: B_0, B_1, B_2 – coefficients of the sample regression model; for explanation see Equations (3 and 4).

The degree of the relationship between two variables (F_p and F_0) was estimated using the correlation coefficient (R), which was equal to the square root of the coefficient of determination. The linear dependence of the separation force on the crushing force is presented using the Minitab Program (version 19.2020.1).

To assess the influence of the cultivar and vegetation conditions on the morphological characteristics (bush height and width), the coefficient of variation of the trait [(CV (%)] was used, which was equal to the ratio of the standard deviation to the average value of the trait. At a value of CV ≤ 10%, the trait for the cultivar would be stable (the variability was weakly expressed), at 10% ≤ CV ≤ 20% there was an average variability of the trait. If the CV value was more than 20%, the variability (dependence) was high.

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Student's (*t*-test) criterion was used to determine the level of significance of the features at a level of significance of $P \leq 0.05$.

The statistical processing of the experimental data was performed using Microsoft Office Excel (version 2010) and Minitab.

RESULTS AND DISCUSSION

Mechanised harvesting with minimal losses is possible under certain parameters of a berry's physical and mechanical properties. If you follow the criteria developed for the black currant, the separation force must be in the range of 0.5–1.5 N, the crushing force should be more than 2 N. These requirements will determine the period of harvest maturity, and the product quality will meet the requirements of the standard GOST 33954-2016 (Yakimenko, Novopokrovsky 1988; Yakimenko 2001; Shavyrkina et al. 2015). The values of the physical and mechanical properties of the berries are subject to significant fluctuations. This primarily depends on the uniformity of the berry maturation and the degree of maturity at the time of the measurement. The mass maturation or technical maturity of the berries in most of the studied cultivars was observed between July 2–3. The total illumination of the plants at the time of measurements was 78 470 to 98 670 lx. The lower part of the bush was the most shaded; about 10% of the total illumination reached the soil surface. In the direction from the outer parts of the shoots to their middle part, the light flux changed slightly (the fluctuations amounted to 4–5% of the total measurement), which contributed to the simultaneous ripening of the berries both in the raceme and along the entire length of the fruit-bearing shoot, this allowed one to obtain high-quality products.

During the harvest period, it was noted that the parameters of the physical and mechanical properties of the berries were not constant, their values decreased by the time of their full or biological maturity, and during this period, the berries gained the maximum amount of sugars and organic acids, the skin density became thinner, and there was often a phenomenon, such as the shedding of berries, which indicated the end of the harvest period. A similar pattern was noted for black currant cultivars by Gurin (2000), Yakimenko (2001), Sazonov and Danshina (2016), Danshina (2017). In the first third of July (2–8), most of the studied red currant cultivars had optimal berry parameters for machine harvesting, with the exception of the Osipovskaya cultivar, which was characterised by a later ripening period (Table 1).

To assess the level of the significant difference in the studied physical and mechanical parameters of the red currant berries, Student's criterion (*t*), the coefficient of variation (CV) and the range of variation (RV) of the characteristics were used. According to Student's criterion, all the differences were significant for the significance of the attribute $P \leq 0.05$. The characteristic relationships between the values of the separation force and the crushing force traits with the values of the coefficient of variation parameter were revealed (Table 2). The higher the instability of the studied parameters, the lower the F_p and F_0 values would fall under certain environmental conditions. A high correlation was found between the coefficient of variation and the range of the variation (Table 3). The maximum trend of the increasing values of the coefficient of variation of the separation force and crushing force from the berries date of removal was observed in Osipovskaya, due to the genetic and morphological differences to the growing conditions.

Table 1. Physical and mechanical properties of the berries

Cultivar	2–3 July		8 July		12 July		15 July	
	F_0	F_p	F_0	F_p	F_0	F_p	F_0	F_p
Asya	1.09 ± 0.24	5.65 ± 1.75	0.82 ± 0.13	8.11 ± 1.06	0.47 ± 0.21	4.97 ± 1.11	0.45 ± 0.18	4.67 ± 0.80
Gazel	1.18 ± 0.30	4.69 ± 1.15	0.88 ± 0.10	6.97 ± 0.68	0.58 ± 0.10	5.33 ± 0.70	0.41 ± 0.11	5.16 ± 1.02
Vika	0.71 ± 0.11	6.44 ± 1.09	0.53 ± 0.19	5.77 ± 0.42	0.38 ± 0.13	5.04 ± 0.66	0.37 ± 0.12	4.55 ± 1.04
Niva	1.31 ± 0.36	8.88 ± 2.08	1.02 ± 0.15	7.72 ± 0.74	0.66 ± 0.08	5.84 ± 0.97	0.6 ± 0.21	5.81 ± 1.01
Osipovskaya	1.78 ± 0.41	10.34 ± 2.45	1.44 ± 0.19	6.77 ± 0.52	1.06 ± 0.22	4.94 ± 1.07	0.44 ± 0.09	4.33 ± 0.98
Jonkheer van tets	0.78 ± 0.15	3.8 ± 1.00	0.9 ± 0.10	4.97 ± 0.64	0.43 ± 0.19	3.95 ± 0.87	0.41 ± 0.17	3.84 ± 0.65
T	3.14		8.55		4.27		4.28	

F_0 – effort to detach the berry from the stalk (N); F_p – press force of crushing the skin (N); T – Student's criterion

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Table 2. Parameters of variability of the separation and crushing force values of the berries in the red currant cultivars

Cultivar	CV		Range of variation	
	F_0	F_p	F_0	F_p
Asya	37.51	23.12	0.64	3.44
Gazel	38.55	15.52	0.77	2.28
Vika	27.76	13.17	0.34	1.89
Niva	32.01	18.46	0.71	3.07
Osipovskaya	42.15	35.50	1.34	6.01
Jonkheer van Tets	34.03	11.65	0.49	1.17

F_0 – effort to detach the berry from the stalk (N); F_p – press force of crushing the skin (N); CV – coefficient of variation

Table 3. Dependence of the coefficient of variation and the range in the variation of the physical and mechanical parameters of the berries

Parameter	R^2	SE
Separation force (CV/RV)	0.8	7.3
Crushing force (CV/RV)	0.91	5.9

R – correlation coefficient; *SE* – standard error

The duration of the harvesting of each cultivar depends on the weather conditions, as well as the rate of decrease in the quantitative indicators, while the reduction of the separation force and the crushing force is not equal. For the effective operation of the berry harvester, it is necessary to predict the duration of the harvest period. According to Gurin's research (2000), to predict the duration of mechanised currant harvesting, it is necessary to measure the parameters of the physical and mechanical properties of the berries of each cultivar within 2–3 years from the moment of entry into fruiting. The average values of the physical and mechanical properties of the berries will be the initial data for calculating the duration of the harvesting. Studies on the parameters of the physical and mechanical properties of berries of 6 red currant cultivars allowed us to determine a correlative relationship between the separation and crushing force indicators, which made it possible to calculate the equation of the duration of harvesting of the red currant cultivars at the beginning of the technical ripening of berries (Figure 3).

The quality of the berries plays a very important role in harvesting.

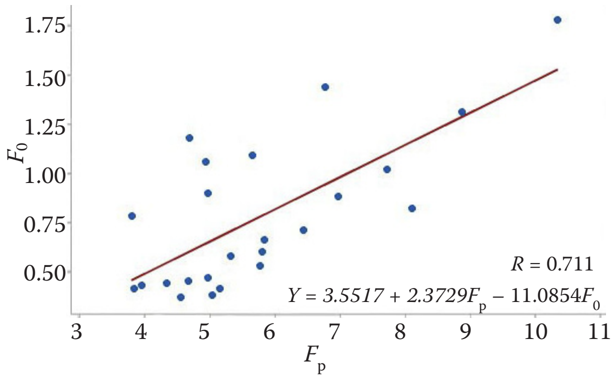

Figure 3. Correlation coefficient between the separation force (F_0) and crushing force (F_p) of the berries of the red currant cultivars

R – correlation coefficient

The quality of the harvested yield depends on the skin strength (SS) and the density of the berries, which determine the resistance of the berries to mechanical damage. The studies showed that in the strength of the berries, all the studied cultivars significantly exceeded the required parameters. The average press force at the stage of the removable (technical) maturity ranged from 7.81 to 13.95 N, by the end of this period, this indicator was not lower than 6 N, which allows us to conclude that there is a sufficiently high stability during the transportation of berries. Niva, Asya and Gazel have the strongest fruit skin (Figure 4).

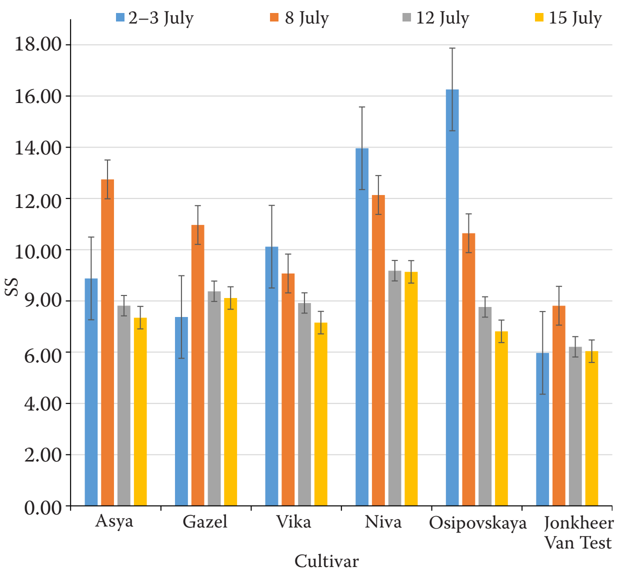

Figure 4. Average berry crushing force

SS – skin strenght

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An important condition for the suitability of berries for machine harvesting is the dry separation of the berries from the stalk, i.e., the strength of the attachment of the fruits (F_0). On average, the separation force during the period of the technical maturity of the berries (3–8.07) varied from 0.53 N in Vika to 1.44 N in Osipovskaya. Later in the maturation process, this indicator gradually decreased by 25–57% (12–15 July). At the same time, by July 15, on average, this indicator, for most cultivars, was below 0.5 N, thus, the optimal mode of operation of the berry harvester would not be possible. The exception was the Niva cultivar, which, during the study period, had optimal values for the studied characteristic, thus, the period of technical maturity of this cultivar was extended more (Table 1).

The set of physical and mechanical properties of the berries is determined by the coefficient of their relative strength, where the separation force and crushing force indicators are taken into account. The value of these parameters for all the studied cultivars during the technical maturity was higher than 0.8, which indicates their suitability for mechanised harvesting. In the previously published reports of Yakimenko and Novopokrovsky (1988) and Yakimenko (2001), the black currant cultivars were characterised by a coefficient higher than 0.8 had a small percentage of damage to the quality of the berries and were recommended for mechanised harvesting.

One of the factors that also has a direct impact on the completeness of the harvest is the biological feature of the structure or growth habit of the bush. According to the black currant research by Nakvasina (2005) and Golovkov (2008), low-growth cultivars with a low fruiting zone are unsuitable for mechanised harvesting; no such data were found in the literature for red currants. The height of the plants of the studied red currant cultivars reached 1.28–1.48 m during the period of technical maturity; this trait is stable and was not characterised by a high phenotypic variability (CV 7.38–12.96%). The tallest cultivars are Niva and Asya. A tall bush provides the zone of placement of the berries the most approximate to the optimal. The width of the bush and the width along the row for some cultivars depend, to a certain extent, on the layout of the bushes, so the values of the coefficient of variation in Gazel and Niva reached values of 18.04–20.26%. Five of the studied cultivars have a compact, optimal bush volume (the coefficient was higher than 0.9, the angle of the branches was in the range of 77–80°, the bush volume was up to 2 m^3). Vika was characterised by the most compact bush shape and stable parameters (CV of 10%). The Osipovskaya bushes had a slightly spreading shape, what is related to the genetic features, so, in the future, for combine harvesting, this cultivar will require additional costs for the spring pruning of bushes (Table 4).

In changing environmental conditions and competitive relationships, a certain degree of variability is constantly observed within the cultivar as a result of the morphological adaptation, and in the process of growth, development and adaptation of the plant to the growing conditions, the scope of the phenotypic variability can either increase or decrease.

In this experiment, the biological (morphological) features of the structure of the bush (height, width, volume, compactness) were quite stable due to a small range of phenotypic variability, which was confirmed by the relatively low values of the coefficient of variation (CV). The biometric values of the bushes' growth habit are mostly determined by the genetic characteristics of the cultivar and are not subject to changes in the environmental conditions (Sazonov, Danshina 2016; Sazonov 2018).

The design feature of the berry harvester is that when the width of the base of the bush is more than 30 cm, the harvesting is accompanied by injury

Table 4. Biometric indicators of the bush habit of red currant cultivars

Cultivar	*H*	CV	*B*	CV	*A*	CV	*V*	*K*
Asya	1.30 ± 0.12	8.32	1.36 ± 0.20	15.22	1.30 ± 0.07	12.76	2.29	0.95
Gazel	1.29 ± 0.15	11.8	1.28 ± 0.25	20.26	1.24 ± 0.14	10.09	1.98	1.00
Vika	1.27 ± 0.12	9.46	1.17 ± 0.09	7.69	1.21 ± 0.10	8.47	1.78	1.08
Niva	1.48 ± 0.11	7.38	1.20 ± 0.21	18.04	1.20 ± 0.13	15.12	2.13	1.23
Osipovskaya	1.31 ± 0.10	12.96	1.52 ± 0.11	14.48	1.42 ± 0.12	10.96	2.78	0.86
Jonkheer van Tets	1.20 ± 0.09	10.81	1.18 ± 0.18	15.21	1.21 ± 0.16	16.81	1.69	1.02

H – height of the bush (m); *CV* – coefficient of variation (%); *B* – width of the bush across the row (m); *A* – length of the bush along the row (m); *V* – volume of the bush (m^3); *K* – compactness of the bush

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(A)

(B)

Figure 5. (A) Red currant harvesting with berry harvester, and (B) harvested berries (Gazel)

to the plants, thus, the losses increase, and the capture area of the conveyor is reduced. The research has shown that all the studied cultivars meet the requirements for this feature (22–25 cm). The range of the trait variation was 1.2–3.6.

The final assessment of the suitability of the red currant cultivars for mechanised harvesting will be determined after testing the berry harvesting equipment. In 2019, as a result of testing the "Joonas-2000" berry harvester (Finland) (Figure 5) on the studied red currant cultivars, it was found that the previously studied limiting and non-limiting signs were fully confirmed in practice. The conclusions made are confirmed in the reports of Dale et al. (1994), Gurin (2000), Yakimenko (2001), Barney, Hummer (2005), Danshina (2017), Sazonov (2018), Kanarskiy, Makarychev (2019).

CONCLUSION

The research has shown that the developed physical and mechanical model of black currant cultivars for mechanised harvesting is applicable to red currants. One of the main criteria for rejecting cultivars are the separation and crushing force indicators, which, in turn, are the basis for predicting the duration of the mechanised harvesting of the red currants.

The efficiency of using the harvester is determined by the selection of the optimal assortment. Red currant cultivars have a number of economically valuable features that also determine the possibility of using the combine: the growth habit (shape) of the bush, the timing of the maturation, the simultaneous maturation of berries in the raceme and the one-dimensional berries. According to the studied technological, biometric and economic-valuable features, Niva, Asya and Vika are considered to be promising cultivars for mechanical harvesting.

Osipovskaya may be suitable for mechanical harvesting only after pruning the bushes, which will incur additional economic costs when growing this cultivar.

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