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Formation of castor productivity depending on the width of row spacing and density of standing

Abstract. The selection of plant species, their varieties, or hybrids and the establishment of their productivity is an urgent necessity today due to the shortage of biofuel production at the world level. The purpose of the study was to identify the influence of technological measures (row spacing width and plant density) on the formation of elements of the crop structure of castor varieties. During 2020-2021, a study was conducted in the field to examine the influence of plant density and row spacing on the elements of the crop structure of castor varieties Khortyts'ka 3 and Olesia in the educational and scientific laboratory "Demonstration field of agricultural crops" of the National University of Life and Environmental Sciences of Ukraine. The following methods were used: theoretical (statistical processing) and practical (descriptive, comparative). The following indicators were evaluated: the weight of 1000 seeds, the number of grains on the plant, and the mass of seeds per plant. The yield of castor seeds of the Khortyts'ka 3 variety was 1.27-1.46 t/ha with a maximum standing density of 50 thousand plants/ha and a row spacing of 70 cm. The seed yield of the Olesia variety was 1.34-1.42 t/ha with the allocation of two most productive options – an option with a row spacing of 45 cm and 37.7 thousand plants/ha and an alternative with a row spacing of 70 cm and a density of 50 thousand plants/ha. The seed productivity of one plant can almost double with a decrease in the density of standing from 50 to 25 thousand plants/ha, while simultaneously forming larger seeds. The weight of 1000 seeds of the Khortyts'ka 3 variety ranged from 268 to 283 grams, and the Olesia variety was 294-316 grams. It was identified that the correlation between seed yield and seed productivity indicators is negative or absent at all, and with the density of standing is positive. The results indicate a high compensatory ability of castor oil varieties Khortyts'ka 3 and Olesia in the establishment of productivity elements at a different density of standing and width of row spacing in the conditions of the Right-Bank Forest-Steppe of Ukraine. This allows for conducting further studies on the influence of sowing parameters in a wider range and using the results obtained for growing castor oil in atypical soil and climatic conditions.

Keywords: elements of the crop structure, weight of a thousand seeds, semi-dwarf varieties, seed yield

INTRODUCTION

Alternative sources of crop raw materials – an urgent need today is due to the necessity of improving energy efficiency and diversifying energy supply sources, producing lubricants, preserving and enriching biodiversity and the environment. Due to the shortage of biofuel production at the world level, it became necessary to find crops that could become alternative food crops, which are now widely used for energy purposes. Along with this, there are a number of issues related to climate change and the need to examine the adaptability of crops in this area for growing in atypical soil and climatic conditions. In this regard, there is a revival of interest in the production of castor oil in Ukraine (*Ricinus communis* L.), which belongs to non-food industrial crops. However, there are a number of questions that need to be investigated and relate to identifying the influence of elements of cultivation technology, in particular, the density of plant standing and row spacing on the realisation of the genetic potential of the crop in conditions that are atypical for the growth and development of this crop.

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In the conditions of climate change, the range of crops that were inherent in individual regions changes, which makes it necessary to examine the features of the establishment of productivity of these crops under the influence of technological techniques for growing them in atypical soil and climatic conditions. The examination of the influence and selection of technological processes that increase the productivity of castor varieties will allow growing crops in the conditions of the Right-Bank Forest-Steppe of Ukraine

Castor oil is a non-food oil crop that originates from tropical and subtropical regions and is well adapted to temperate climates. Castor (*Ricinus communis*) can grow up to 10-12 meters in tropical regions and is a perennial, but in temperate latitudes, it is grown as an annual crop with a height of 1-3 m (Salihu *et al.*, 2014). Castor has been cultivated for centuries to produce the oil from its seeds (Ribeiro *et al.*, 2016). Castor seeds contain 40 to 60% fat, which consists of a mixture of triglycerides of various saturated and unsaturated fatty acids, with a substantial predominance of ricinoleic acid, the content of which can reach 89% (Mallah & Sahito, 2020). Despite its wide adaptability, global castor oil production is concentrated in only a few countries, among which India is the undisputed leader, as according to FAO data for 2020, almost 90% of world-produced castor seeds were grown there (Food and Agriculture Organisation..., 2022).

The increase in castor oil production worldwide over the past decade is a clear indication of the wide range of applications of this oil and its derivatives in various industries (Mubofu, 2016). Today, the oil is used in agriculture, food processing, electronics, and for the manufacture of textiles, paper, plastic, rubber, cosmetics, perfumes, medicines, paints, inks, additives, lubricants, and biofuels(Mallah & Sahito, 2020).

The productivity of castor crops in annual cultivation is limited. The yield of castor oil reaches 1.5-2.9 t/ha with repeated fruit harvesting, and record yields (up to 5 t/ha) can be obtained by growing it as a perennial crop (Koutroubas *et al.*, 1999).

Castor oil is characterised by high adaptability to weather and soil conditions. Although it is a long-day plant, for which, increasing the duration of the light season by more than 12 hours contributes to the formation of female flowers, castor oil also grows well in regions with a photoperiod of at least 9 hours and good lighting (Salihu *et al.*, 2014).

In tropical regions, castor oil is grown as a perennial crop, but only annuals are suitable for mechanised harvesting. In the Mediterranean region and moderately warm zones, it is grown as a spring-summer crop, mainly because of its heat-loving nature, especially when sprouting and lowering temperatures in winter. In these regions, castor oil is sown mainly in April, when the soil temperature reaches 16-17°C. Low soil temperature prolongs the process of germination and emergence of seedlings, and frosts below -8°C lead to the death of even the most cold-resistant genotypes in a few hours (Zanetti *et al.*, 2017).

The suitability for industrial cultivation of this crop depends on the main climatic restrictions, i.e. the temperature and duration of daylight hours, regardless of the presence of moisture in the soil and the supply of nutrients that can be provided in the future by the cultivation technology (Patanè *et al.*, 2019).

The purpose of the study – establish the influence of plant density and row spacing on the elements of the crop structure and castor productivity. The goal of the study was to assess the influence of elements of cultivation technology on the yield of the crop under study and to choose the conditions for rational management of agrotechnological processes and measures for stable optimisation of the productivity of alternative oilseeds.

MATERIALS AND METHODS

Field research was conducted in 2020-2021 in the educational-scientific laboratory of the Department of Crop Growing "Demonstration field of agricultural crops" of the National University of Life and Environmental Sciences of Ukraine. According to the complex of weather-climatic conditions, the research area can be attributed to the Forest-Steppe agro-climatic zone.

Weather conditions on the territory of the Forest-Steppe part of the Kyiv region during the research period were characterised by increased average monthly temperatures in summer compared to long-term indicators and substantial deviations in monthly precipitation in certain months (Fig. 1).

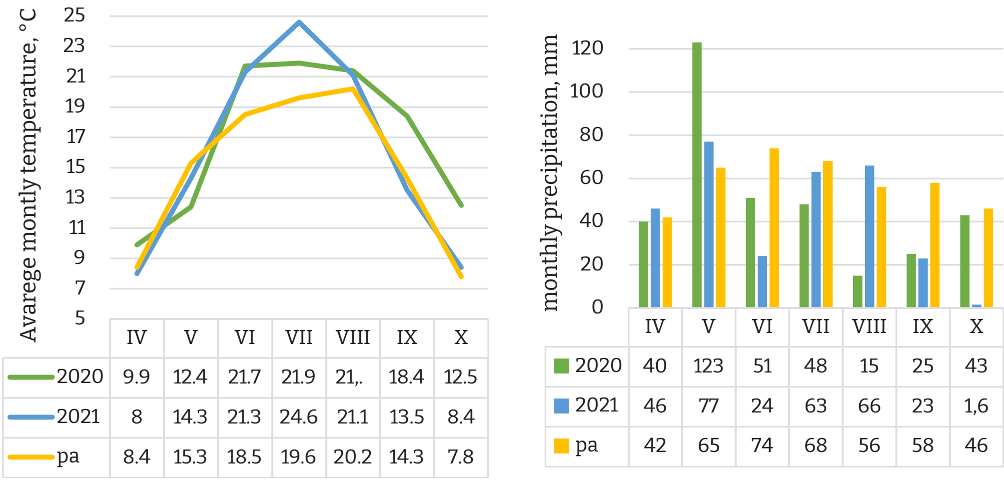

Figure 1. Average monthly air temperature (A) and monthly precipitation (B) during the castor growing season (April-October), 2020 and 2021

Note: pa – perennial value

Weather conditions in 2020 were motley, as the air temperature in some months substantially exceeded the perennial value, and in others, it was lower. The average monthly temperature in April of this year exceeded the perennial value by 1.5°C and was 9.9°C, which enabled the beginning of sowing in the third decade of April. The average monthly temperature in May was 2.9°C lower than the perennial value and was 12.4°C, that is, the growing process of castor oil at the initial stage of development slowed down. In the summer months, the air temperature was higher than perennial values because in June the excess was 3.2°C, in July – 2.3°C, and in August – 1.2°C. The air temperature was substantially higher in the autumn months of the growing season, which contributed to the ripening of castor fruits – in September it was 3.9°C warmer, and in October – 4.7°C.

During the period from April to October 2020, 345 mm of precipitation fell, which is 64 mm less than the perennial value for this period of time, but their distribution was heterogeneous – in May, almost twice the normal amount fell, and in subsequent months there was less precipitation. In August and September of this year, 15 and 25 mm of precipitation fell, respectively, which was 27-43% of the norm, that is, in combination with a substantially higher air temperature during this period, there could be a lack of moisture in castor crops.

The air temperature during the growing season of castor in 2021 at the initial stages was close to the perennial value. In April, the average air temperature was 0.4°C below normal and was 8°C, in May it was lower by only 1.0°C (14.3°C), and from June to August substantially exceeded the perennial value. In June 2021, the average monthly air temperature was 21.3°C (+2.8°C to norm), in July – 24.6 (+5°C to the norm), and in August – 21.1°C (+0.9°C to the norm). September was colder than usual, as the air temperature averaged 13.5°C, which is 0.8°C less than theperennial value , and in October it was 0.6°C above the norm – 8.4°C.

The amount of precipitation for April-October 2021 was 300.6 mm, which is 108.4 mm lower than the annual average, and their distribution during the growing season was also heterogeneous. In the spring months, precipitation was close to the perennial value and in June only 24 mm fell, which is 50 mm less than normal. In July and August, the amount of precipitation was close to normal, but at high air temperatures, the humidification regime could substantially differ from the perennial value. The amount of precipitation in September (23 mm) was 35 mm lower than the perennial value, and in October there was almost no effective precipitation (the amount of precipitation for the month was 1.6 mm).

The air temperature and precipitation varied over the years of research, but due to the biological characteristics of castor, these conditions were acceptable and favourable for growing this crop.

The soil of the experimental site is grey forest coarse-dusty light-loamy in granulometric composition. Humus content 2.54±0.18%, easily hydrolysed nitrogen content 72±8 mg, mobile phosphorus 98±25 mg, exchange potassium 70±22 mg per 1 kg of soil; pH_{KOH} 5.8-6.1, the sum of the absorbed bases is 10-15 mg×eq/100 g of soil. Soil density at steady state is 1.1-1.2 g/cm^3, the humidity of persistent wilting is 10.2%. The depth of ground water is 2-4 m.

The scheme of plant placement during sowing is developed considering the sowing suitability of castor seeds at the level of 95% (Table 1).

Table 1. Field experiment scheme

Factor A	Factor B	Factor C	Plant placement scheme, cm×cm
Variety	Row spacing width, cm	Standing density, thousands of plants/ha	
A1. Khortyts'ka 3	B1. 45 cm	25.0	45×85
		37.5	45×57
		50.0	45×42
	B2. 70 cm	25.0	70×55
		37.5	70×36
		50.0	70×27
A2. Olesia	B1. 45 cm	25.0	45×85
		37.5	45×57
		50.0	45×42
	B2. 70 cm	25.0	70×55
		37.5	70×36
		50.0	70×27

The predecessor is winter wheat. After harvesting the predecessor, stubble peeling was conducted. Winter ploughing was conducted in the I-II decade of September to a depth of 22-24 cm and fertilisers were applied in the norm $P_{45}K_{45}$ (superphosphate 18%, potassium chloride 60%). According to the physical ripeness of the soil (PV 55-60%), moisture was closed in the spring using a light tooth harrow (BZSL-1,0). On the day of sowing, disking was conducted to the depth of sowing and N_{30} was applied(ammonium nitrate – 33.4%) in pre-sowing cultivation. Seeds were treated with fundazole (benomyl) at a rate of 2.5 kg/t before sowing. Seeds were sown to a depth of 6-8 cm at a soil temperature of 10-12°C at 10 cm. The date of sowing in 2020 is April 28, in 2021 – May 7. Sowing was conducted manually at a given standing density. Plant protection products were not applied during the growing season. All elements of the cultivation technology, with the exception of the subjects, were the same throughout the experiment.

The repetition rate of the experiment is fourfold. The total area of one plot is 31.5 m^2 (4.2 m × 7.5 m for row spacing of 70 cm; 4.5 m × 7.0 m for row spacing of 45 cm), accounting – 25.2 m^2 (4.2 m × 6.0 m for row spacing of 70 cm; 4.5 m × 5.6 m for row spacing of 45 cm).

Sampling and assessing of samples

In each variant, 10 plants were selected on the side brushes during the full fruit ripeness phase. The results obtained for each of the indicators were tested for normality according to the Shapiro-Wilk criterion (Razali & Wah, 2011). In the case when the variational series did not correspond to the normal distribution, the number of samples was increased.

The seed mass from each plant was determined by collecting all the ripe castor fruits and removing the shells. All ripe seeds from the plant were weighed with an accuracy of 0.1 g, then the average value was determined.

The thousand seeds weight was determined by weighing two samples of 500 seeds each, followed by calculating the arithmetic mean. If the discrepancy between the mass of the samples and the arithmetic mean exceeded 3%, the third sample was taken. It was determined with an accuracy of 0.1 g.

The number of fruits was determined by counting all ripe fruits on the plant that contained at least one ripe seed.

The seed yield was determined by collecting all seeds from the registered plot and converting the value in t/ha to a basic seed humidity of 12%.

Statistical processing of the results was performed using STATISTICA 13.0 software tools and the built-in Microsoft Excel analysis package. A variance analysis was performed, and the Fischer criterion of the smallest substantial difference (HIP_{05}) was used to determine the substantial difference between the options and the influence of factors on performance elements. Fisher's LSD post-hoc analysis module for homogeneous groups was used at a substantiality level of 0.05, and the groups were assigned letters starting with *a* to assess the difference (or similarity) between the variants. The empirical results obtained correspond to the normal distribution (Gaussian distribution).

Regression analysis was performed, linear and polynomial models were developed, and Pearson coefficients of determination and pairwise correlation were determined to establish the dependences of seed mass and plant density. Pearson pair correlation coefficients for pairs of performance elements were set by the Correlation matrix software with the definition of p-values for each indicator.

RESULTS AND DISCUSSION

The structure of castor yield is determined by such elements as the density of standing, the mass of seeds per plant, the mass of 1000 seeds, and the number of seeds per plant, which depends on the number of fruits on the main and side brushes.

The results of the analysis of variance (ANOVA) of crop structure indicators are presented in Table 2. The factual standing density was additionally determined to consider the influence of intraspecific competition on the establishment of castor productivity elements.

Table 2. Dispersion analysis of elements of the castor crop structure

Main factors	SWpP		TSW		FpP		SDH		SY	
		Part[1], %		Part[1], %		Part[1], %		Part[1], %		Part[1], %
Variety(V)	*	0.9	**	90.5	**	3.9	ns	0.0	*	15.1
Row spacing width (RS)	ns	0.0	*	0.2	ns	0.0	ns	0.0	ns	0.6
Standing density (SD)	**	98.2	**	8.7	**	95.4	**	99.9	**	52.2
Interactions										
V × RS	ns	0.1	ns	0.0	ns	0.1	ns	0.0	ns	0.6
V × SD	*	0.5	**	0.3	ns	0.2	ns	0.0	**	19.3
RS × SD	*	0.3	*	0.2	*	0.3	ns	0.0	**	11.8
V × RS × SD	ns	0.0	ns	0.1	ns	0.0	*	0.05	ns	0.3

Note: Part[1] – the part of involvement in the establishment of variance due to factors and interactions; * – indicates a substantial difference at the level of $p<0.05$; ** – indicates a substantial difference at the level of $p<0.001$; ns – there is no substantial difference at the level of p = 0.05; SWpP – seed weight per plant; TSW – thousand seeds weight; FpP – fruits per plant; SDH – standing density on harvest; SY – seed yield

The conducted variance analysis of the indicator of standing density on harvest shows that the factor of standing density is dominant (99.9% of the impact), so the decrease or variation in the number of plants in the field is due only to this factor, that is, the influence of other factors is levelled. The results obtained allow for linking the density of standing during germination (and, accordingly, the quantitative seeding rate) with the density of standing at the time of harvesting.

The variety factor was dominant among the main factors in the establishment of the thousand seeds weight, while in the establishment of seed yield, the number and seed weight per plant, its part of involvement in the variation of productivity elements was in the range of 0.9-15.1%, which sometimes (the seed weight per plant) was at the level of statistically unreliable influence (p-value was close to 0.05). The width of row spacing, as an independent factor, contributed to an increase in the thousand seeds weight (from 1 to 5 g), where its share of influence was 0.2%, and in other cases, p-value exceeded 0.05, that is, this factor in the study did not affect the mass of seeds from the plant, the number of fruits per plant, and yield, but manifested itself in interaction with the density of standing (RS×SD ratio in Table 2), especially in the establishment of seed yield (11.8% of the effect). The standing density factor had a dominant effect on the mass of seeds per plant (98.2%), the number of fruits per plant (95.4%), and the establishment of seed yield caused 52.2% variability. The relationship of factors and their influence on the establishment of individual productivity indicators varied, but in total did not exceed 1-2% (with the exception of yield), and the interaction of all factors at once was statistically unreliable in all elements of the crop structure, except for the standing density on harvest, where its influence was limited to 0.05% variation.

The weight of castor seeds from one plant varied from 28.1 to 54.4 g under the influence of factors of variety and density of standing but did not depend at all on the factor of row spacing width. Notably, the standing density factor caused 98.1% of all variations in seed mass from the plant, while the variety factor caused only 0.9%. About 0.3% of substantial deviations were caused by the interaction "row spacing width*standing density", which was manifested in a substantial difference between the variants of standing density of 37.5 thousand units/ha in the Olesia variety with row spacing of 45 and 70 cm, in favour of the 45 cm variant, where an average of 37.5 g of castor seeds were formed on the plant, and on the 70 cm variant – 35.5 g (Fig. 2).

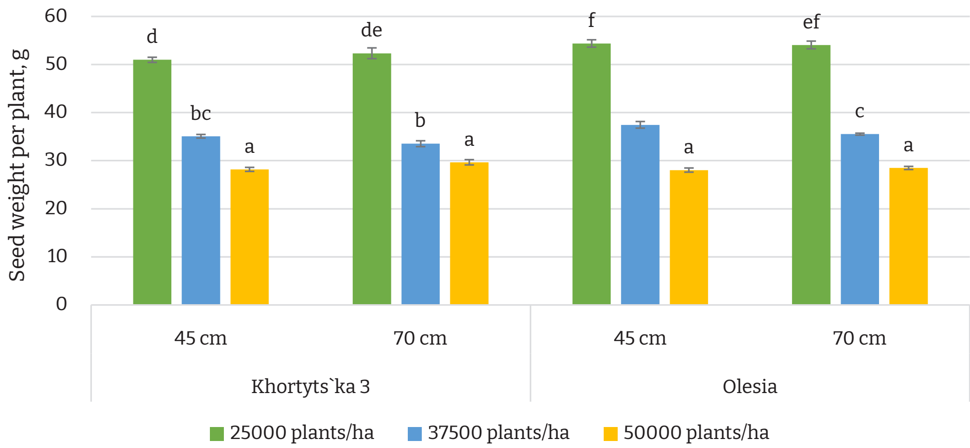

Figure 2. Seed weight (g) per plant

Note: The same letters indicate that there is no substantial difference between the values at the level of p=0.05, columns without letters differ substantially from all other options, columns with different letters also differ substantially qt HIP_{05}

Based on the results of the analysis of variance and subsequent evaluation according to the criterion of HIP_{05} there are six groups of similarities (*a-f*) and one separate variant, which differed in the value of the mass of seeds from the plant and amounted to 37.5 g.

Notably, in the Khortyts'ka 3 variety, there was no statistically substantial difference between variants with the same standing density, but different row spacing widths ($\Delta < HIP_{05}$), therefore, with a standing density of 25 thousand plants/ha, this variety formed an average of 51-52 g of seeds per plant, with a standing density of 37.5 thousand pcs./ha – 34-35 g, and the smallest at a standing density of 50 thousand plants/ha – 28-30 g. The Olesia variety on average formed 54 g of seeds with a standing density of 25 thousand plants/ha, which is 2 g more than in the Khortyts'ka 3 variety on similar variants. With a standing density of 37.5 thousand plants/ha, the Olesia variety formed 37.5 g of seeds with a row spacing width of 45 cm and 2 g less seeds with a width of 70 cm, that is, the difference was substantial because it exceeded HIP_{05}. Therewith, with a standing density of 50 thousand plants/ha, the seed weight per plant was also 28 g, without a difference in the width of row spacing and the Khortyts'ka 3 variety on similar variants.

The formation of castor fruits and seeds is a response of sowing to the availability of life factors, so it is possible to develop empirical models describing the relationship between the mass of seeds from the plant and the density of standing. According to the studies by Cordeiro *et al.* (2019) and Fiorese *et al.* (2016), the regression equation is unique for each variety and may vary depending on the growing conditions. Castor is a very plastic plant, so in addition to the linear model, nonlinear ones, in particular, the polynomial model, can also be used to describe dependencies. The second-degree polynomial relationship describes the relationship between the density of standing and the mass of seeds from a plant substantially more accurately than the linear function, and the coefficient of determination (R^2) in this case, it is close to one (Table 3).

Table 3. Polynomial and linear model of the relationship between seed mass from a plant and standing density (x)

Variety	Row spacing width, cm	Polynomial model ($R^2 = 1$)	Linear model	R^2 for a linear model
Khortyts`ka 3	45 cm	$y=0.0288x^2 - 3.0732x + 109.79$	$y= -0.9111x + 72.256$	0.9505
	70 cm	$y=0.0478x^2 - 4.4935x + 134.79$	$y= -0.9067x + 72.516$	0.8734
Olesia	45 cm	$y=0.024x^2 - 2.8553x + 110.74$	$y= -1.0531x + 79.454$	0.9436
	70 cm	$y=0.0369x^2 - 3.7883x + 125.79$	$y= -1.0233x + 77.734$	0.9367

Note: The variable x is represented as thousands of plants/ha

Therewith, the alternative linear model for each class and row spacing width has a high coefficient of determination (from 0.8734 to 0.9505), that is, the Pearson correlation coefficient (modulo) is in the range of 0.935-0.975, which is a strong relationship close to functional. The available data (standing density options) is not sufficient for the unambiguous selection of the priority model. The polynomial model accurately describes the results obtained and allows identifying the most similar data sets, for example, the equations for varieties

Khortyts'ka 3 and Olesia with row spacing of 45 cm have more in common than the option of 70 cm compared to 45 cm within the variety. The alternative linear model, on the contrary, better describes the varietal features of seed mass formation from a plant depending on the density of plant standing, without considering the width of row spacing (since the coefficient for variable and independent coefficient are similar within the variety). This problem requires corrective studies with an extension of the range of standing densities and a reduction in the step between options. Based on the results obtained by Severino *et al.* (2017), there is generally no association between row spacing and individual productivity of castor plants in the temperate growing zone, whereas, in conditions of unstable humidity, this is important. Therewith, planting crops closer limits the availability of life factors, especially moisture, so induced water stress can cause a decrease in the mass of seeds from the plant, both due to a decrease in the number of fruits per plant and due to a decrease in the mass of 1000 seeds (Alves *et al.*, 2019; Mazurenko *et al.*, 2020).

Mass of 1000 seeds (seed size)

The varieties investigated are characterised by different masses of thousands of seeds. A thousand seeds weight of the Khortyts'ka 3 variety, depending on the seeding rate and row spacing width, varied in the range of 268-283 g, and in the Olesia variety – from 294 to 316 g (Fig. 3).

It was identified that all factors and their individual interactions influenced the establishment of the mass of 1000 seeds, in particular, it was the varietal factor that caused the highest variation – 90.5%, and the density of standing – 8.7%, while the total influence of all other factors was 0.8%.

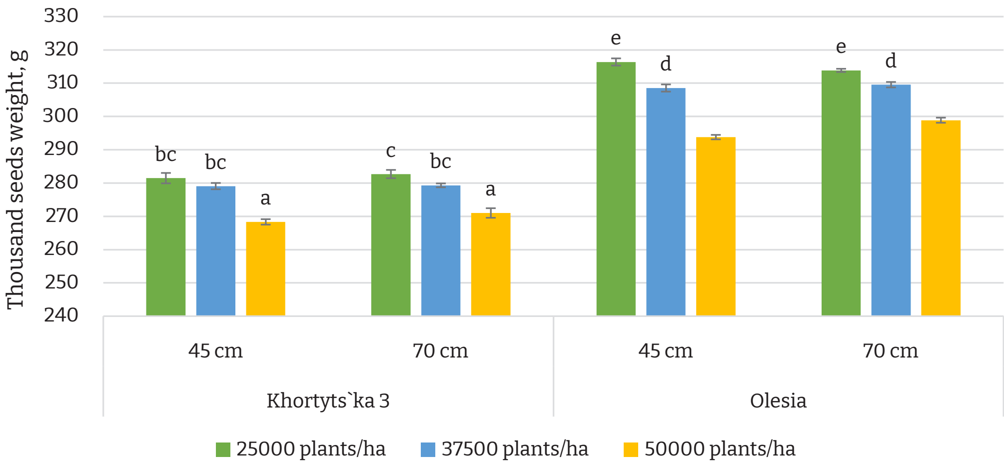

Figure 3. Weight of a thousand castor seeds (g)

Note: The same letters indicate that there is no substantial difference between the values at the level of p=0.05, columns without letters differ substantially from all other options, columns with different letters also differ substantially at HIP_{05}

The mass of 1000 seeds in the Khortyts'ka 3 variety did not statistically differ in variants with a standing density of 25 and 37.5 thousand plants/ha and different standing densities, because it was 279-283 g, that is, the variants belonged to the same similarity group (group *c*). An increase in the density of standing up to 50 thousand plants/ha led to a substantial decrease in the weight of 1000 seeds to 268-271 g – by an average of 4.2%, which allowed distinguishing a block of variants into a group *a*. In the variety Khortyts'ka 3, the difference in the average mass values of 1000 seeds with the same density of standing, but different width of row spacing is within the margin of error of the average, which indicates the inertia of this variety to the spatial placement of plants in relation to the reaction to seed size. Therewith, with a row spacing of 70 cm, the seed 1-3 g larger is formed but this is not a statistically substantial difference.

The Olesia variety had a similar tendency to form a mass index of 1000 seeds, but the influence of standing density was more pronounced. The largest mass of 1000 seeds was formed at a standing density of 25 thousand plants/ha and averaged 316 g with a row spacing of 45 cm and 314 g for 70 cm, however, the difference was statistically insubstantial, so these two options belong to the group *e*. On variants of standing density of 37.5 thousand plants/ha, a substantial decrease in the mass of 1000 seeds was observed, but without a substantial difference between the width of row spacing. On average, the Olesia variety with a standing density of 37.5 thousand plants/ha formed a mass of 1000 seeds at the level of 309-310 g. According to the results of the preliminary analysis of variance, it was identified that 0.2% of the total variance is due to the factor of row spacing width, so only in the Olesia variety with a standing density of 50 thousand plants/ha, there was a difference between variants with different row spacing widths. With a row spacing of 45 cm, castor crops formed seeds with a weight of 1000 seeds at the level of 294 g, and with a row spacing of 70 cm, on average, 5 g heavier – 299 g.

The mass index of 1000 seeds is quite plastic, but the model that describes the dependence of this indicator on the density of standing will vary depending on the variety and growing conditions. Usually, an increase in the density of standing leads to a decrease in the mass of 1000 seeds, that is, the relationship is inversely linear. However, if there is a factor regulating the microclimate in the ground layer (the presence of mulch, cover culture, etc.), then this relationship can be polynomial and until a certain indicator of standing density, the mass of 1000 seeds can grow (Cordeiro *et al.*, 2019; Honchar *et al.*, 2020).

The castor fruit is a three-seeded capsule, so it is more expedient to indicate exactly the number of fruits as an element of the crop structure, and not the number of seeds. The seed inside the fruit develops synchronously, so it is very rare for only one or two seeds to form in the capsules. The number of fruits from one plant has a clear dependence on the density of standing, which causes 95.4% of the variation in this indicator. About 3.9% of the variation in the number of fruits on plants was caused by the variety factor and 0.3% by the interaction of standing density and row spacing width, while other factors and their interactions had a statistically unreliable effect. Confirmation of the results of the analysis of variance is graphically displayed (Fig. 4), where it can be seen that in one variety with the same density of standing and width of row spacing, there is almost no difference in the number of fruits that ripen and form seeds.

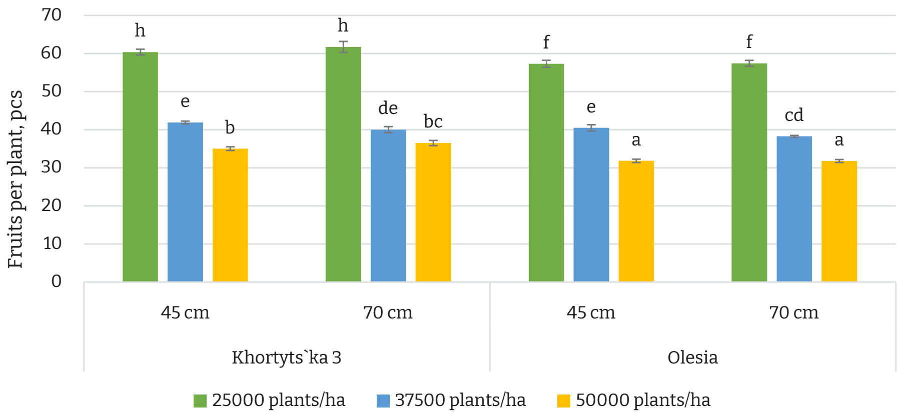

Figure 4. Number of fruits from the castor plant

Note: The same letters indicate that there is no substantial difference between the values at the level of p=0.05, columns without letters differ substantially from all other options, columns with different letters also differ substantially at HIP_{05}

The influence of the variety factor was manifested in an increase in the number of fruits in the Khortyts'ka 3 variety compared to the Olesia variety at the minimum and maximum standing density. The Khortyts'ka 3 variety formed an average of 60-62 capsules with a standing density of 25 thousand plants/ha, and when thickened to 50 thousand plants/ha, it reduced their number to 35-37 pieces. Therewith, about 57 and 32 fruits were formed in the Olesia variety, respectively. This trend continued at a density of 37.5 thousand plants/ha, but due to the high variation in the number of fruits, there was almost no statistically substantial difference between varieties and row spacing.

Larger seeds of the Olesia variety (by weight of a thousand seeds) are formed in a smaller number than in the Khortyts'ka 3 variety, so the previously established seed weight per plant in both varieties is similar with the same parameters of row spacing width and density of standing, the process of forming these indicators is a reflection of the compensatory ability in crop formation, and both varieties vegetated on the verge of realising the genetic potential in the given conditions. Given this fact, the yield formation and its range were substantially narrower than usual for agricultural crops. According to the results received by (Cordeiro *et al.*, 2019), the presence of additional vegetation, even from other ecological niches leads to a substantial decrease in the number of fruits per plant (a decrease of up to 18%), and in the case of intraspecific competition in production crops, the decrease can reach 50%, that is, an increase in the density of standing is levelled by a decrease in individual productivity of the plant.

The yield of castor oil consists of all the considered elements of the crop structure. The variants of standing density investigated in the experiment had a negative correlation with other elements of productivity, but to assess the influence of this factor, the total seed yield should be analysed (Table 4).

Table 4. Castor seed yield in 2020-2021 (average), t/ha

Variety	Spacing width, cm	Standing density of thousands of plants/ha	Yield, t/ha	Similarity groups
Khortyts`ka 3	45 cm	25.0	1.29±0.02	*ab*
		37.5	1.32±0.01	*bcd*
		50.0	1.43±0.02	*fh*
	70 cm	25.0	1.31±0.02	*abc*
		37.5	1.27±0.01	*a*
		50.0	1.46±0.02	*h*
Olesia	45 cm	25.0	1.35±0.01	*cde*
		37.5	1.42±0.02	*fh*
		50.0	1.39±0.02	*ef*
	70 cm	25.0	1.36±0.01	*de*
		37.5	1.34±0.01	*cd*
		50.0	1.42±0.01	*fh*
LSD_{05} = 0,04 t/ha				

Note: The same letters indicate that there is no substantial difference between the values at the level of p=0.05, different letters indicate a substantial difference at HIP_{05}. Similarity groups are marked by the yield from the lowest to the highest *a* – the lowest, *h* – the most productive

During statistical processing of the yield of castor varieties, seven groups of similarity are determined from *a* to *h* – from low-yielding to high-yielding options. The most productive options (group *h*) in the variety Khortyts'ka 3, there were combinations of row spacing width of 70 cm and standing density of 50 thousand plants/ha with a yield of 1.46 t/ha of seeds; and row spacing width of 45 cm with the same standing density, where an average of 1.43 t/ha of seeds was formed. Notably, this variety with a standing density of 25 and 37.5 thousand plants/ha formed substantially fewer seeds for both variants of row spacing. On average, 1.27-1.32 t/ha was formed on these variants, which allowed distinguishing these variants into low-productive groups – *a* and *b*.

In the Olesia variety, two variants were also included in the highly productive group *h* – a combination of row spacing width of 70 cm and standing density of 50 thousand plants/ha with a yield of 1.42 t/ha and a variant with row spacing width of 45 cm and standing density of 37.5 thousand plants/ha with the same yield. Notably, the yield of this variety in the experiment varied less than in the Khortyts'ka 3, because the minimum value was 1.34 t/ha, and the maximum value was 1.42 t/ha. Most of the combinations of the elements of the technology provided an acceptable level of yield and belonged to intermediate groups *d*, *e*, and *f* .

The high yield of variants with a higher density of standing (37.5 and 50 thousand plants/ha) and with a small difference between these variants is a consequence of the adaptation of plants to growing conditions and the establishment of habit depending on the existing life factors. Many researchers confirm the thesis that with certain parameters of standing density, the yield of castor oil transfers into a so-called plateau, that is, further compaction of crops does not lead to an increase or decrease in yield, but this range is unique for each variety and soil and climatic conditions (Cordeiro *et al.*, 2019; Sampaio *et al.*, 2019).

Correlation between elements of castor oil productivity

The data series describing the performance indicators of the two varieties are similar, so they can be used in the same array to determine Pearson correlation coefficients (Table 5).

Table 5. Paired Pearson correlation coefficients between elements of the castor crop structure

	SWpP	TSW	FpP	SD	SY
SWpP	1	0.41*	0.98**	-0,023	-0,001
TSW		1	0.21^{ns}	-0.39*	0.00^{ns}

Table 5, Continued

	SWpP	TSW	FpP	SD	SY
FpP			1	−0.95**	−0.47**
SD				1	0.61**

Note: * – correlation between traits is statistically substantial at the level of 0.05<p>0.01; * * – correlation between traits is statistically substantial at the level of p<0.01; ns – correlation between elements of the crop structure is statistically unreliable at the level of p<0.05; SWpP – seed weight per plant; TSW – thousand seeds weight; FpP – fruits per plant; SD – standing density; SY – seed yield

The relationship between standing density and castor productivity elements is negative, i.e. they decrease with increasing density, but this does not apply to the relationship with yield (r=0.61). Notably, the relationship between standing density and yield has a greater impact compared to other productivity elements, so increasing standing density increases yield, despite the fact that the seed weight per plant and the number of fruits decreases (Angraeni & Purwati, 2022). The yield of castor seeds had a negative correlation with the mass of seeds from the plant and the number of fruits, and there was no correlation with the mass index of a thousand seeds.

CONCLUSIONS

Varieties Khortyts'ka 3 and Olesia have many common features in the establishment of productivity because they are genetically approximate, so the establishment of quantitative indicators of productivity (seed weight per plant, number of fruits) is similar. The developed polynomial and linear models of the dependence of seed mass on standing density indicate similar mechanisms of seed mass establishment from the same plant in the investigated varieties. The main factor influencing the variation in seed mass indicators from the plant, the number of fruits per plant, was the density of standing since the share of this factor in these productivity indicators exceeded 95.4%. Therewith, the influence of standing density on yield was 52.2%, and a substantial share was occupied by interactions of standing density with the varietal factor and standing density, which was not observed in individual productivity elements. In general, varieties were characterised by similar parameters of crop structure elements with the same combinations of standing density and row spacing width, as evidenced by multiple comparisons, but in some variants, the difference was substantial, so certain options were more effective by a set of features. The maximum yield of castor seeds of the Khortyts'ka 3 variety was 1.46 t/ha, and in the Olesia variety – 1.42 t/ha. Notably, the yield variation of the Olesia variety is much smaller, which indicates its adaptability to a wide range of different growing conditions, and the higher productivity of the Khortyts'ka 3 variety indicates the available unused yield potential. Therefore, further research on optimising the parameters of sowing and plant density is promising, given the efficiency and low cost.

A promising area for future research will be the adjustment of crop parameters with the development of practical models for the establishment of productivity indicators and their reduction to the level of a variety to realise the biological potential of productivity in conditions of a limited growing season of castor.

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Формування продуктивності рицини залежно від ширини міжрядь та густоти стояння

Анотація. Підбір видів рослин, їх сортів чи гібридів та формування їх продуктивності є гострою необхідністю сьогодення у зв'язку з дефіцитом виробництва біопалива на світовому рівні. Мета роботи полягала у виявленні впливу технологічних заходів (ширина міжряддя та густота стояння рослин) на формування елементів структури врожаю сортів рицини. Впродовж 2020-2021 рр. у польових умовах проводили дослідження з вивчення впливу густоти стояння рослин та ширини міжряддя на елементи структури врожаю рицини сортів Хортицька 3 та Олеся в навчально-науковій лабораторії «Демонстраційне поле сільськогосподарських культур» НУБіП України. Використовували такі методи: теоретичні (статистична обробка) та практичні (описові, порівняльні). Проводили оцінку наступних показників: маса 1000 насінин, кількість плодів на рослині, маса насіння з рослини. Урожай насіння рицини сорту Хортицька 3 становив 1,27-1,46 т/га з максимумом при густоті стояння 50 тисяч рослин/га і ширині міжряддя 70 см. Урожайність насіння сорту Олеся становила 1,34-1,42 т/га з виділенням двох найпродуктивніших варіантів – опція з шириною міжрядь 45 і 37,7 тисяч рослин/га та альтернативна з шириною міжрядь 70 см і густотою 50 тисяч рослин/га. Насіннєва продуктивність однієї рослини може зростати майже вдвічі при зниженні густоти стояння з 50 до 25 тисяч рослин/га, з одночасним формуванням крупнішого насіння. Маса 1000 насінин сорту Хортицька 3 становила від 268 до 283 грам, а сорту Олеся становила 294-316 г. Встановлено, що кореляція між урожайністю насіння та показниками насіннєвої продуктивності є негативною, або взагалі відсутньою, а з густотою стояння позитивною. Результати досліджень вказують на високу компенсаційну здатність рицини сортів Хортицька 3 та Олеся при формуванні елементів продуктивності за різної густоти стояння та ширини міжрядь в умовах Правобережного Лісостепу України. Це дозволяє проводити подальші дослідження з вивчення впливу параметрів сівби у більш широкому діапазоні та використовувати отримані результати за вирощування рицини у нетипових для неї ґрунтово-кліматичних умовах

Ключові слова: елементи структури врожаю, маса тисячі насінин, напівкарликові сорти, урожайність насіння