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Comparative analysis of oil flax varieties according to economically valuable traits in the Steppe zone of Ukraine

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Abstract. Interest in oil flax has been growing in recent decades. Linseed oil is a fast-drying oil and it is traditionally used in the production of linoleum, paints and coatings. Due to their content of essential polyunsaturated acids and vitamins, the growing use of flax seeds and oils in food and medicine has significantly increased the volume of its cultivation in different countries. This article presents the main research results for 2018−2020 of a large group of varieties of oil flax of Zaporizhzhia breeding for economically valuable traits. The purpose of research is to establish the genotypes that form the highest yields and oil content in arid conditions of the Steppe zone of Ukraine. It was found that the most productive year was 2020 due to more favorable temperatures and even distribution of precipitation during the growing season of oil flax. It was found that the yield of oil flax had a high correlation coefficient with weather conditions (r = 0.67) especially from precipitation in May-June (r = 0.60). A detailed study of the correlation between yield and habit traits and the main economically valuable traits revealed a close direct correlation between oil flax yield and seed weight per 1 plant (r = 0.99), yield and number of lateral stems per plant (r = 0.93), yield and number of bolls and seeds per 1 plant (r = 0.77), yield and weight of 1,000 seeds (r = 0.73), yield and duration of the growing season (r = 0.65). According to the results of three-year research, the highest yield was obtained from the variety Vodohrai 1.79 t ha^{-1}. The highest oil content and oil yield per hectare were formed by varieties Vodohrai 50.1% and 0.80 t ha^{-1}, Zolotystyi 49.7% and 0.76 t ha^{-1}, Aisberh 48.3% and 0.72 t ha^{-1}.

Key words: oil flax, variety, duration of the growing season, habit, element of productivity, yield, oil content, oil yield per hectare, correlation.

INTRODUCTION

Oil flax *Linum humile* Mill is an annual plant 40−60 cm tall, which is grown to obtain seeds with high oil content. Other than oil flax, cultivated flax also includes long flax. Long flax is grown for high quality fiber. Compared to the habitat of long flax, oil flax occupies a much larger area, which is due to its wider ecological potential and lower demand for soil moisture (Diakov, 2006).

Oil flax has been known to man as a cultivated plant since the ancient times and it has played an important role in the economic and social development of mankind (Zohary et al., 2012; Zelentsov, 2017; Zhuchenko Jr & Rozhmina, 2000; Krugla, 2002). In recent decades, interest in the cultivation of oil flax has grown significantly in different countries around the world, as evidenced by numerous publications, both with focus on genetic and plant breeding as well as with agronomic, botanical and biochemical focus (Özkutlu et al., 2007; Lafond et al., 2008; Desta & Bhagwan, 2014; Delesa & Choferie, 2015; Pecenka et al., 2016; Tretjakova et al., 2018; Kiryluk & Kostecka, 2020).

Linseed oil is categorized as a fast-drying oil and it is a necessary component of paints, inks, varnishes, linoleum, and anti-corrosion coatings. It is used in medicine, cosmetology and nutrition (Oomah, 2001; Kiralan et al., 2010; Peshuk & Nosenko, 2011; Kraevska et al., 2019; Lykhochvor et al., 2022). The main component of the oil - linolenic acid - is a main unsaturated acid, which determines its high biological activity and ability to dry quickly (Diakov, 2006; Peshuk & Nosenko, 2011).

In Ukraine, interest in this crop has also grown significantly in recent years, thanks to its drought resistance and profitability. Market dynamics indicate a steady increase in linseed oil demand and the rapid expansion of sown areas (Statistichniy byuleten, 2017−2021). Oil flax is successfully grown in all soil and climatic zones of Ukraine due to its biological properties and ecological adaptability (Makhova & Polyakov, 2012; Vishnivska, 2013; Voytovych & Shuvar, 2018). However, the main growing areas are located in the Steppe zone. Despite the fact that up to 20% of sown areas can be saturated with oil flax, this crop in Ukraine remains niche. In the general structure of oilseed crops it has a share of about 1%, and its share in the structure of oilseed production is at 0.3%. Oil flax occupies a small share in the domestic market segment of oilseed crops. It is grown for exporting seeds, which are then bought by EU member states, Egypt, China, Turkey and other countries (Linseed, mustard. Oilseed crops production, 2017).

Oil flax ripens well at a sum of temperatures of 1,600−1,850 °C during the growing season. Seedlings tolerate frost up to -2, -3 °C. The optimal sowing rate of flax seeds in the Steppe zone is 4−6 million units ha^{-1}. It is recommended to sow early so that the seeds ripen in warm weather. It is sown in the usual row method to a depth of 3−4 cm. Soils should have a neutral reaction. Growing season of oil flax is 90−130 days. It belongs to the group of crops with a short growing season. But during prolonged rains in ripening stage if oil flax does not dry out it might even 'grow back', so desiccation is required. Oil flax plants grown in drier areas have better developed lateral roots, which penetrate into the soil to greater depths. Researchers who grow oil flax agree on the high plasticity of the crop when growing it in different climatic, weather and soil conditions (Makhova & Polyakov, 2012; Nakamoto & Horimoto, 2016; Kalenska & Stolyarchuk, 2018; Voytovych & Shuvar, 2018).

To increase crop yields, it is necessary to create and implement high-yielding varieties. Total number of oil flax varieties in the State Register of Plant Varieties Suitable for Distribution in Ukraine is constantly increasing. About half of the Ukrainian varieties were created at the Institute of Oilseed Crops of the National Academy of Agrarian Sciences of Ukraine. At present, according to official statistics in Ukraine, 65−75% of sown areas are occupied by oil flax varieties of Zaporizhzhia breeding (State register of plant varieties, 2016−2020). To increase the efficiency of plant breeding in the Zaporizhzhia breeding school of oil flax, a parametric model was created, explaining the parameters of traits and properties of the variety that will create a genotype that meets modern production requirements (Poliakova, 2015).

Our research aimed to establish the genotypes of oil flax, which form the highest yields and oil content in arid conditions of the Steppe zone of Ukraine to increase the economic efficiency of cultivation.

MATERIALS AND METHODS

Research was conducted in 2018−2020 in the city of Zaporizhzhia (North-Western part of the Zaporizhzhia oblast) at the experimental site of the Department of Genetics and Plant Resources of Zaporizhzhia National University. Soil of the experimental site was ordinary chernozem, of medium strength and of low humus, with humus content in the arable layer of 0−30 cm - 3.4% (according to State standard of Ukraine 4362: 2004. Soil quality indicators of soil fertility), available nitrogen (N - by Cornfield) - 70−80, mobile phosphorus (P_2O_5 - by Chirikov) - 92−101, exchangeable potassium (K_2O - Chirikov) - 148−165 mg kg^{-1} of soil, soil pH - 6.5−7.0 (State standard of Ukraine 4362: 2004).

Setting up the experiments and conducting research was carried out according to generally accepted field experiment methods in agriculture and crop production (Littl & Hills, 1981; Dospekhov, 1989). Agricultural techniques in the experiments complied with the recommendations (Lyakh & Poliakova, 2008).

In the years of research, weather conditions for temperature and precipitation had some deviations from the long-term average, which allowed to fully establish their impact on the growth and development of flax plants and the realization of the appropriate amount of yield. Data on the amount of precipitation and temperature in the years of research compared to average multi-year indicators, is given in Figs 1 and 2.

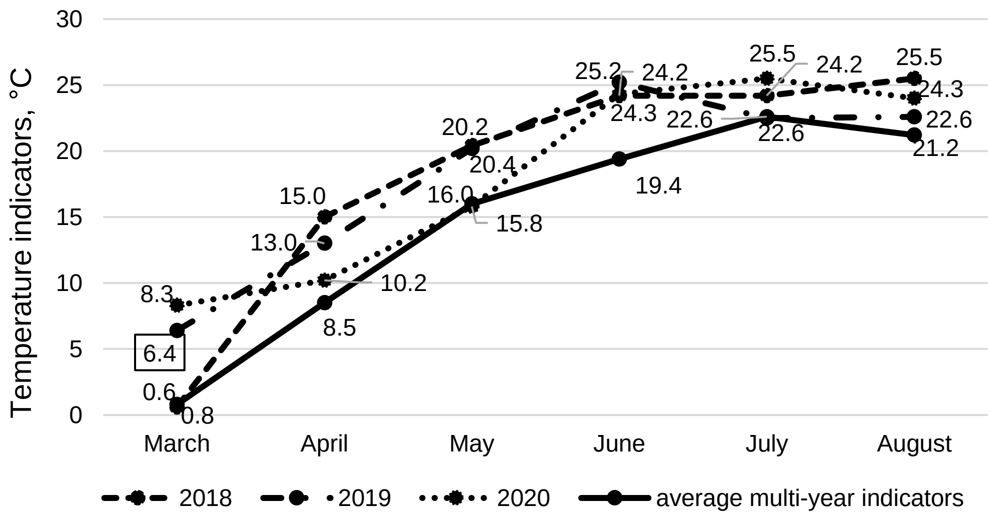

Figure 1. Temperature indicators during the growing season of oil flax (2018−2020).

Experiments used material from the collection of the Department of Genetics and Plant Resources of Zaporizhia National University - varieties Pivdenna Nich (year of registration 2000), Debiut (2000), Aisberh (2001), Orfei (2001), Zolotystyi (2005), Kivika (2007), Vodohrai (2010), Patrytsii (2018).

Plant description was written down according to generally accepted methods (Lyakh & Poliakova, 2008). Plot placement was randomized. Plot area constituted 25 m^2, flax predecessor was winter wheat and basic soil tillage consisted of plowing. Sowing was conducted in the first ten days of April. All measurements and observations were conducted three times.

To determine the characteristics of growth and development of flax plants a set of studies, calculations and phenological observations was conducted (Lyakh & Poliakova, 2008):

– length of vegetation period was determined between seedling and full maturity stages;

– phases of growth and development of flax were noted down: seedling stage, stem extension stage, budding stage, flowering stage, and full maturity. Beginning of the stages s was established when it occurred in 10% of plants, and stage completion for 75% of plants;

– the number of bolls per plant and the number of seeds per plant was counted in 25 plants;

– seed yield was determined continuously from each plot;

– weight of 1,000 seeds was calculated according to standard methods;

– oil content of seeds was determined according to DSTU 7577: 2014;

– statistical processing of the obtained data was carried out on the programs ‘Microsoft Office Excel’ and the modern statistics software package ‘STATISTICA 10’;

– obtained data was subject to mathematical analysis using variance and correlation calculations (Littl & Hills, 1981; Dospekhov, 1989).

RESULTS AND DISCUSSION

As can be seen from the figure, in terms of temperature indicators in all years of research, there was a surplus of them over the long-term average values (Fig. 1). The biggest deviations in temperature happened in 2018, especially in the first months of the growing season in the seedling and stem extension stages. That year, the temperature exceeded the averages by 6.5 °C in April and 4.4 °C in May. And in 2020, the temperature was closest to the long-term average and the deviations of its indicators were 1.7 °C in April and -0.2 °C in May. The most favorable temperature indicators during the ‘budding-flowering-boll formation’ period in June were also noted in 2020. The deviation in temperature from the average long-term values was 1.9 °C, while in 2018 it was 4.6 °C, and in 2019 it was 5.8 °C. Thus, 2020 turned out to be the most favorable year in terms of temperature indicators.

In 2018 there was also the most uneven distribution of precipitation throughout the growing season (Fig. 2). A significant surplus was noted only in March before sowing the crop and in July at the stage of seed ripening. And in April, May and June, the amount of precipitation was significantly less than the long-term average. Despite the fact that the total amount of precipitation in 2018 for the entire growing season of oil flax was 288 mm, which is more than in 2019 (238.6 mm) and in 2020 (211.2 mm), due to their uneven distribution and high air temperature it marked the lowest height of flax plants and their yield. It is important to emphasize that the biological peculiarity of oil flax is that it has slower growth at the beginning stages of development, a small leaf blade and a weakly spread root system, so the lack of moisture in the beginning stages of growth and development is very critical for this crop. Fig. 2 shows that in 2019 and 2020, precipitation during crop growth was closer to the long-term average and was more evenly distributed from March to August.

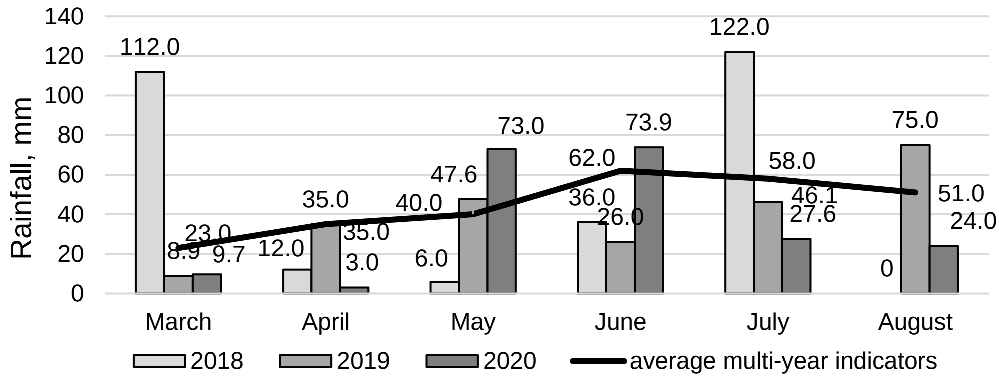

Figure 2. Amount of precipitation during the growing season of oil flax (2018–2020).

Studied weather conditions that happened during the research years significantly influenced the growth, development and formation of the productivity of oil flax plants.

Due to the increased temperature and insufficient amount of precipitation, the shortest growing season of oil flax plants was recorded in 2018, 79–97 days. In the most, favorable year 2020, this figure was 88–105 days, depending on the variety, and the average values for three years were 84–101 days. As can be seen from the data in Table 1 the studied varieties differed among themselves in the length of the growing season, both in terms of the average and across different years. But in general, it can be noted that the two varieties Kivika and Debiut belong to earlier varieties that ripen in 84 and 86 days, respectively, which is 8 and 6 days earlier than the standard variety Pivdenna Nich, while varieties Orfei and Zolotystyi have a growing season of 3 and 9 days longer than the standard variety. Longevity of the growing season, for any variety, is an important biological trait, that can be of great practical importance (Table 1).

Table 1. Length of the growing season of oil flax varieties in the conditions of the Steppe zone of Ukraine (2018−2020)

Varieties	Years			Average value
	2018	2019	2020	
Pivdenna Nich (standard)	88	92	95	92
Debiut	81	87	90	86
Aisberh	86	90	93	90
Orfei	91	95	98	95
Zolotystyi	97	102	105	101
Kivika	79	85	88	84
Vodohrai	92	93	97	94
Patrytsii	87	91	94	91
LSD_{05}	1.1	1.7	2.0	

Studied varieties also differed in other economically valuable traits (Table 2). We have studied the following traits: plant height, number of stems, number of bolls, number of seeds per 1 plant, weight of seeds from 1 plant, weight of 1,000 seeds.

Traits of plant habit are decisive in the breeding for high productivity. Habitual traits of flax plants include such basic external traits as the height of the plant and the number of lateral stems. In breeding studies, the length of the technical part of the stem is also taken into account in a more detailed description. Plant height is a trait that significantly depends on changes in weather and climatic conditions. In our research, the lowest rates for all varieties were obtained in 2018, and the highest in 2020. Most researchers agree that the formation of the height of flax plants is greatly influenced by external conditions that develop during the period of intensive plant growth. As can be seen from Table 2, the maximum value of plant height on average over the years of testing - 62.3 cm - was formed by the variety Vodohrai, and the minimum 49.7 cm by the variety Kivika. Average value of the plant height of the studied varieties for the years of research was 55.6 cm. Stem of oil flax is an important useful part of the plant because it contains valuable fiber. In addition to performing the main conductive and mechanical functions, flax stem to some extent performs the function of temporary storage of reserve carbohydrates and proteins, and it also contributes to the formation of products of photosynthesis (Diakov, 2006). Therefore, the height of flax plants is given a lot of attention when creating varieties. In our experiments, the varieties Vodohrai were significantly higher than the standard by 8.0 cm, Zolotystyi by 5.7 cm and Orfei by 4.1 cm.

Table 2. Economically valuable traits of oil flax varieties in the conditions of the Steppe zone of Ukraine (average value for 2018–2020)

Varieties	Traits					
	plant height, cm	number of stems, pcs	number of bolls, pcs	number of seeds from 1 plant, pcs	weight of seeds from 1 plant, g	weight of 1,000 seeds, g
Pivdenna Nich (standard)	54.3	2.7	6.9	51.9	0.40	7.7
Debiut	50.8	2.4	6.8	50.7	0.35	6.9
Aisberh	56.2	2.8	8.8	65.8	0.48	7.3
Orfei	58.4	2.6	7.4	55.7	0.39	7.0
Zolotystyi	60.0	3.1	8.3	62.0	0.49	7.9
Kivika	49.7	2.3	8.2	61.7	0.37	6.0
Vodohrai	62.3	3.1	8.5	63.8	0.51	8.0
Patrytsii	52.9	2.7	7.7	57.7	0.41	7.1
Average value	55.6	2.7	7.8	58.7	0.43	7.2
LSD_{05}	1.2–2.3	0.08–0.12	0.23–0.32	0.8–1.7	0.03–0.06	0.11–0.20

Number of stems per 1 plant averaged from 2.3 to 3.1, depending on the variety. At the same time, the standard variety Pivdenna Nich averaged 2.7 stems. Varieties Zolotystyi and Vodohrai exceeded the standard variety the most, by 0.4 stems, and the lowest numbers for this trait were in the varieties Debiut and Kivika. This trait is important because it directly correlates with indicators of the yield structure, such as the number of bolls and seeds per one plant. Thus, for the Zolotystyi variety, the number of bolls and seeds per plant was 8.3 and 62.0 pcs. And for the variety Vodohrai - 8.5 and 63.8 pcs. These varieties exceeded the Pivdenna Nich standard variety by 1.4 and 10.1 pcs. and 1.6 and 11.9 pcs, respectively. In addition, the Aisberh variety stood out by the formation of a large number of bolls (8.8 pcs) and seeds in them with (65.8 pcs) a relatively small number of side stems (2.8 pcs). Variety Debiut had the lowest indicators for the studied elements of the yield structure, namely: number of bolls - 6.8 pcs, number of seeds - 50.7 pcs, and number of stems - 2.4 pcs. And Orfei and Kivika varieties formed a lot of bolls and seeds in them, however, due to the low weight of

1,000 seeds, the indicator 'mass of seeds from 1 plant' was lower than that of the standard variety Pivdenna Nich by 0.01 g and 0.03 g.

'Weight of 1,000 seeds' indicator is important for flax since it is a small-seeded crop. In the presented range of flax varieties, it ranged from 6.0 to 8.0 g, and for standard variety it was 7.7 g. On average for three years of research, this figure was 7.2 g. It was found that the smallest seed belonged to Kivika variety (6.0 g). Vodohrai (8.0 g) and Zolotystyi (7.9 g) varieties had larger sized seeds. Therefore, they can be used in further breeding work as a source of large fruited seeds, because this trait is important when cleaning seeds from weeds.

An important summarizing indicator, which depends on the number of bolls and seeds, as well as their size, is the 'mass of seeds from 1 plant'. This indicator, on average over the years of research, ranged from 0.35 to 0.51 g, depending on the variety, and the average value was 0.43 g. The highest indicators were in the varieties Vodohrai (0.51 g), Zolotystyi (0.49 g) and Aisberh (0.48 g), which exceeded the standard variety Pivdenna Nich (0.40 g) by 0.11 g, 0.09 g and 0.08 g, respectively.

Yield is one of the most important traits of growing for any crop. The difference for this trait is the high degree of its integration. According to our data the average yield by variety over the years of research was 1.49 t ha^{-1}. The most productive year was 2020 with an average of 1.69 t ha^{-1}, then 2019 - 1.59 t ha^{-1} and the lowest yield in 2018 was 1.20 t ha^{-1}. This indicator directly correlates with the weather conditions described above, during the growing season. If we consider the varieties in comparison, the most productive in all years of research was variety Vodohrai (1.79 t ha^{-1}). Varieties Zolotystyi (1.72 t ha^{-1}) and Aisberh (1.68 t ha^{-1}) also significantly exceeded the variety-standard. Debiut and Kivika varieties produced lower yields than the standard Pivdenna Nich variety. Highest yield for the years of research was 2.13 t ha^{-1} for the variety Vodohrai in 2020 (Table 3).

Table 3. Yield of the oil flax in the conditions of the Steppe zone of Ukraine, t ha^{-1} (2018−2020)

Varieties	Years			Average value
	2018	2019	2020	
Pivdenna Nich (standard)	1.17	1.50	1.54	1.40
Debiut	0.97	1.31	1.38	1.22
Aisberh	1.28	1.81	1.94	1.68
Orfei	1.21	1.44	1.49	1.38
Zolotystyi	1.30	1.86	2.01	1.72
Kivika	1.12	1.39	1.43	1.31
Vodohrai	1.33	1.92	2.13	1.79
Patrytsii	1.24	1.52	1.59	1.45
Average value	1.20	1.59	1.69	1.49
LSD_{05}	0.07	0.10	0.11	

We experimentally proved that the yield of oil flax had a fairly high correlation coefficient with weather conditions in the years of research ($r = 0.67$). At the same time, the change in temperature indicators in comparison with the average long-term values did not play a significant role, both for the entire growing season and in individual months. Another trend that we noted happened in terms of rainfall and its distribution over the growing season. The amount of precipitation that happened during the entire growing season between April and August had a correlation coefficient $r = 0.52$. A closer correlation was observed between yield and the amount of precipitation that happened between May and June ($r = 0.60$). In our opinion, this period of growth and development of oil flax plants needs the most moisture and it is crucial for the formation of seed yield. Similar results were obtained by A. Shuvar (2021) only in the conditions of another natural zone, namely, the Western Forest-Steppe of Ukraine.

We analyzed the correlations between yield, habit traits, and productivity elements. A close direct correlation was established between oil flax yield and plant height (r = 0.83), number of side stems (r = 0.93), number of bolls and seeds per plant (r = 0.77), weight of a 1,000 seeds (r = 0.73). Closest relationship was found between seed yield and weight per plant (r = 0.99), and the average correlation with the length of the growing season (r = 0.65). According to our data, the length of the growing season is closely related to the height of plants (r = 0.84), the number of side stems (r = 0.83) and the weight of 1,000 seeds (r = 0.77), and the average relationship is between total weight of seeds from 1 plant and yield (r = 0.65). The existence of a close correlation was established between the habit traits, namely, the height and number of lateral stems, and the following elements of productivity: seed weight per 1 plant (r = 0.83) and (r = 0.93) and weight of 1,000 seeds = 0.79) and (r = 0.91), respectively. Estimation of the strength of the links between the elements of productivity revealed the existence of a linear close correlation between the number of bolls and the number of seeds (r = 0.99), the number of seeds per plant and seed weight per plant (r = 0.75) and between weight of the seeds from 1 plant and weight of a 1,000 seeds (r = 0.75). Our results are confirmed by the data of O. Kurach (2016) and O. Rudik (2019), who studied the relationship between yield and economically valuable traits of oil flax. In our research, we paid more attention to establishing the links between yield indicators with the length of the growing season, habit traits, and elements of productivity.

One of the main indicators of flax seed quality is its oil content. We found that the oil content in the seeds of varieties on average over the years of research was between 43.9 and 50.1%. Vodohrai (50.1%), Zolotystyi (49.7%) and Aisberh varieties (48.3%) had the highest oil content. They exceeded the standard variety by 5.3%, 4.9% and 3.5%, respectively. Highest oil content in the seeds was observed in 2020. In that year, all studied varieties had higher oil content than the average. In 2018, on the contrary, there was a much lower oil content in the seeds. As mentioned above, 2018 had extremely unfavorable dry weather conditions, which also affected the accumulation of oil in the seeds (Fig. 3).

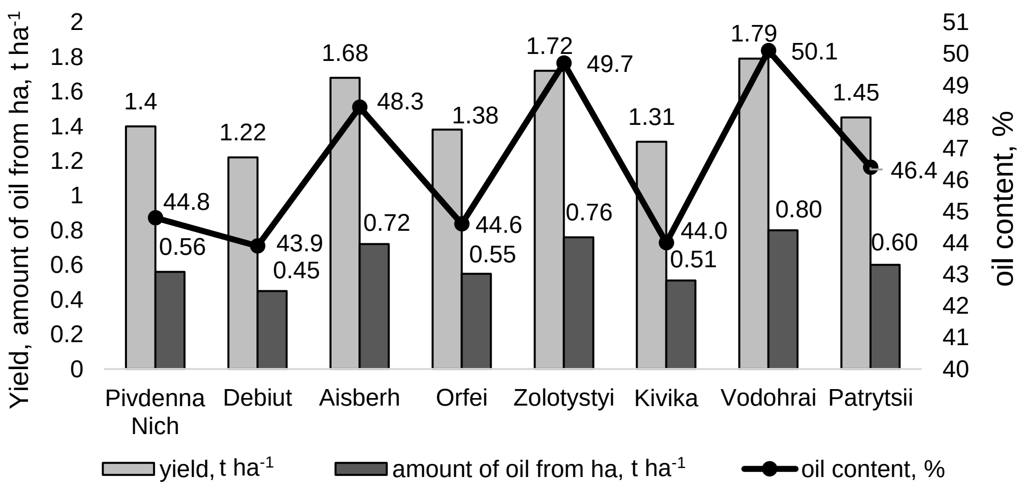

Figure 3. Yield, oil content and oil yield of different varieties of oil flax in the conditions of the Steppe zone of Ukraine (2018–2020).

The indicator 'oil yield per hectare' is very emblematic in the cultivation of oilseed crops is the indicator 'oil yield per hectare'. It is derived from the yield and oil content and characterizes a particular variety's economic value. Varieties Vodohrai (0.80 t ha^{-1}), Zolotystyi (0.76 t ha^{-1}) and Aisberh (0.72 t ha^{-1}) had the highest oil yield per hectare (Fig. 3). Varieties Debiut and Kivika did not exceed the standard variety.

According to other researchers, oil flax varieties of Zaporizhzhia breeding in other natural and climatic zones of Ukraine also formed high oil content in seeds and oil yield per hectare (Kurach, 2016; Rudik, 2019; Shuvar, 2021).

High productivity sources are needed to increase flax yields and to increase oil yield per hectare. Oil flax breeding to create varieties with the highest possible level of productivity, takes into account a complex set of physiological, morphological, biological and other traits that determine the level of yield in specific growing conditions and use a variety model with defined parameters of different traits (Poliakova, 2015).

These results indicate that the varieties Vodohrai, Zolotystyi and Aisberh, had higher seed weight per 1 plant, plant height, number of side stems, over the standard variety and other varieties, which allowed them to form the highest yields. They are also characterized with high oil content. That is why, in our opinion, these three varieties are potential genetic sources of economically valuable traits for further breeding work.

CONCLUSION

Comprehensive analysis of eight commercial varieties of oil flax of Zaporizhzhya breeding was undertaken for the main economically valuable traits in contrasting weather conditions for three years in 2018, 2019, 2020. When conducting a correlation analysis, it was found that the yield of oil flax had a high correlation coefficient with weather conditions in the years of research; most significantly yield depended on precipitation. A close direct correlation was established between oil flax yield and plant height, number of side stems, number of bolls and seeds per plant, weight of 1,000 seeds, and the closest relationship was found between yield and weight of seeds from 1 plant.

Top indicators of economically valuable traits of the studied varieties were obtained in 2020. The highest yield, oil content and the highest oil yield per unit area was noted for varieties Aisberh, Zolotystyi and Vodohrai.

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