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DYNAMICS OF FERTILITY INDICATORS OF LIGHT-CHESTNUT SOIL AND OIL FLAX PRODUCTIVITY UNDER BOGARIAN CONDITIONS OF SOUTHEAST KAZAKHSTAN

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SUMMARY

The suitable research aims to ascertain the optimum dose of mineral fertilizers and methods of soil processing and preparation for successful flax (*Linum usitatissimum* L.) cultivation in the semi-arid conditions of the Almaty Region, Kazakhstan, focusing on achieving high crop productivity with good seed quality. Agrochemical investigations also employed modern devices and widely accepted methods. Studying parameters, such as total humus, labile humus, nitrate nitrogen, mobile phosphorus, exchangeable potassium, soil composition density, structural-aggregate composition, and moisture supply, ensued using specific techniques. The study observed an enhancement in nitrate nitrogen content in the soil, from an initial level of 11–19 mg/kg to 36–91 mg/kg during flax harvest in all experimental variants. On the contrary, the mobile phosphorus exhibited a decline in the soil from the beginning of crop vegetation until harvest; however, determining the available phosphorus in different practices showed medium, high, higher, and very high. Moreover, a decline in exchangeable potassium content (from 344–446 mg/kg to 175–215 mg/kg) emerged during the flax crop across all the experimental variants. The application of mineral fertilizers NPK at the rate of 60:60:30, with the application of a growth regulator Ecorost at the rate of 2 liters per ton of seeds, and employing a flat-cut treatment (10–12 cm) on light chestnut soil in the semi-arid zone with super dry season of Almaty Region, resulted in the highest flax yield in cv. Karabalykskaya (410 kg/ha).

Keywords: Flax (*Linum usitatissimum* L.), mineral fertilizers, plowing, flat-cut tillage, zero tillage, nitrate nitrogen, mobile phosphorus, exchangeable potassium, productive moisture, productivity

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Key findings: The presented research comprising flax (*Linum usitatissimum* L.) culture, used different doses of mineral fertilizers with varying tillage. The effect of tillage methods and application of mineral fertilizers on agrophysical and agrochemical indicators of soil and linseed yield were promising.

INTRODUCTION

Recently, there has been a tendency in farming communities toward cultivating flax (*Linum usitatissimum* L.) due to a consistent global rise in demand for flax-based products. Flax has extensive uses across various sectors of the national economy. The vegetable fat content is one of the chief quality indicators of the flax seeds. Currently, the oil of modern flax cultivars reaches 50% or more. However, despite the successes achieved, the potential for further selection in productivity remains since the biological limit of the flax oil content (60%) still needs full achievement (Brach *et al.*, 2016). On a global scale, the total cultivated area with oil flax crops ranges from 2.5 to 3.2 million ha, with seed yields reaching 1.9 to 2.7 million tons (Khodyankov *et al*., 2013).

Flax imposes precise requirements on the availability of readily digestible nutrients in the soil due to its relatively underdeveloped and small root system. It exhibits slow growth and development with limited leaf surface area, resulting in low competitive ability during its initial growth stages. Accordingly, to achieve higher yields, it becomes decisive to ensure an adequate supply of nutrients to flax crops right from the beginning and early stages of vegetation (Cicu, 2017). However, the oil flax crop requires fewer nutrients and responds favorably to soil fertility and fertilizers versus grain crops, such as wheat, rye, and barley. On average, flax plants consume 5–8 kg of nitrogen, 1–3 kg of phosphorus (P_2O_5), and 4–6 kg of potassium (K_2O) to produce 100 kg of seeds (Dvurechensky *et al.,* 2011; Soethe *et al*., 2013).

Flax crops absorb uneven and small amounts of nutrients during the germination and budding phases, reaching a peak during the flowering stage. For instance, nitrogen and phosphorus consumption increases as the flax crop approaches the flowering period (Rahimi and Bahrani, 2011; Lukomets *et al.,* 2013). However, flax has a higher nitrogen demand than any other below-ground nutrient. With sufficient availability of other nutrients, nitrogen contributes to rapid plant growth, robust above-ground biomass formation, and enhanced seed yield with good quality (Vinogradov *et al.,* 2010). In flax, the nitrogen requirement is not usually high before the branching phase; however, the critical periods for nitrogen utilization correspond with the branching-flowering transition. Insufficient nitrogen during that critical period significantly reduces seed yield. In humid climate and cool weather in May-June, nitrogen fertilization at early stages become obligatory for flax, preferably through pre-sowing applications (Garkusha *et al.,* 2011).

In cold and rainy seasons, additional fertilization is primarily necessary for flax crops when a slowing down of ammonification and nitrification processes in the soil occurs, which leads to nitrogen deficiency in plants. Most nitrogen fertilizers are applicable as the primary fertilizer typically treated during spring pre-sowing cultivation of flax (Naliukhin, 2015). However, excessive nitrogen nutrition during the first half of the flax growing season can result in lodging, reduced drought tolerance, compromised fiber quality, and ultimately decreased productivity (Lashchev, 2016). Late-maturing flax cultivars exhibit slower growth and development than early-maturing ones; however, they are lodging-resistant. Consequently, late-maturing cultivars require higher nitrogen fertilizer doses than early-maturing genotypes under the same soil fertility conditions.

According to past studies, the optimal nitrogen dosage for flax crops varies across regions of Russia, ranging from N20 to N120 (Zadvornev and Porsev, 2015). However, the appropriate dosage depends on factors like cultivation zone, soil type and fertility, weather conditions, yield level, and other environmental factors (Bushnev, 2011). In the foothill-steppe zones of Crimea for flax crops, the nitrogen economical dose does not exceed N35 when applied during pre-sowing tillage (Gapienko *et al.,* 2009). In Argentina, an increased flax seed yield surfaced with increasing nitrogen levels from 40 to 120 kg per ha (Sanchez and Flores, 1999). For Iran, Brazil, and Chile, applying nitrogen doses of 100–150 kg/ha contributes to improved flax seed yield ranging from 2.0 to 2.5 t/ha (Bertil *et al.,* 2009). For the oil flax crop, the recommended phosphorus fertilizers for application are at dosages from 45 to 90 kg of active substances per hectare, depending on the soil's phosphorus content. It is highly effective to introduce fertilizer in the form of phosphate, such as superphosphate and nitrophoska, into rows during spring sowing, resulting in a yield increase of 0.3 t/ha in oilseed crops (Kolomeichenko, 2007).

In modern agriculture, nutrient deficiencies should not limit yields. Ensuring this requires maintaining soluble forms of phosphorus and potassium in the soil at the levels anticipating strong fertilizer responsiveness since freshly applied fertilizers do not yield as much as soil reserves. Flax crop incurs harmful effects from uneven distribution of fertilizers in the soil, resulting in unequal stem coloration, varying plant heights and branching, and prolonged ripening. The recommended N:P:K ratio in the soil is approximately 1:2:2 for poor soils and 1:3:3 for rich soils (Michkina and Popova, 2012). According to Sanin *et al.* (2006), in the Middle Volga Region, the most effective dosage is N (40–60) and P (60), and for soils with low potassium content, the dosage is N (40–60) P (60) K (40–60) per hectare. In South Ukraine, the dark chestnut soils proved the most productive with an economically efficient dose of mineral fertilizers (N105P10K20) used for the oil flax crop (Bidnina, 2013). The resulting seed yield and oil were 1.67 t/ha and 0.66 t/ha, respectively, 56% and 57% higher than the unfertilized control soil.

Fertilizer application improved growth and development, extended the growing season, increased the number of lateral shoots, and improved the crop structure indicators (number of capsules per plant and 1000-seed weight), eventually resulting in an increased flax seed yield of 1.86 t/ha (Vinogradov and Kuntsevich, 2015). On leached chernozem soil in Krasnodar, the highest increase in oilseed crop yield emerged when applying N30 during sowing (0.35 t/ha) or a combination of N30 at sowing and N30 as a top dressing in the flowering phase (0.42 t/ha), representing a 15.1% and 18.1% increase in seed yield, respectively, compared with the unfertilized control. The doses of N30P30 and N30P30K30 in spring application increased the seed yield by 0.30 t/ha (12.9%) and 0.25 t/ha (10.8%), respectively, while nitrogen feeding (N30) at the flowering phase increased the seed yield by 0.20 t/ha (8.6%). In the central non-chernozem region, on sandy-podzolic, light-loamy soils, the highest flaxseed yield (1.45 t/ha) resulted from a mineral fertilizer dosage of N45P60K90 per hectare.

Results on studying the effects of direct seeding technology (without disturbing the soil through tillage) compared with the traditional soil preparation and crop cultivation technology (shallow non-moldboard tillage to a depth of 10–12 cm) and seed treatment with a complex microbial preparation (CMP) on the indicators of yield and quality of *Linum usitatissimum L*. seed under the insufficient moisture conditions in the steppe Crimea have been formulated (Gongalo, 2020). Their findings revealed that using CMP in cultivating oil flax without tillage (no-till technology) enhanced the flax crop yield and excelled the no-till and traditional farming systems.

In almost all the regions of oilseed flax cultivation on all soil types and using mineral and organic fertilizers, a significant increase manifested in seed yield; although, increases may vary depending upon the cultivar and environmental conditions (Pershakov *et al.,* 2021). The application of mineral fertilizers at a dose of N60:P60:K60 per ha provided a maximum oil harvest of 709.7 kg/ha, which exceeded the indicators of the control variants by 149.4 kg/ha (Brazhnikov *et al.,* 2019).

In recent years, flax was the only spinning crop cultivated on a production scale in Russia. Various branches of the economy need natural fiber raw materials – textile and space industry, military-industrial complex, medicine, and automotive industry. This situation is because the cotton imports, due to increased purchase prices, become economically unjustified. Moreover, its supplies will sharply reduce in the future as cotton-producing countries set up their processing. At the same time, over the last decade alone, the area under flax in the country has decreased more than twice. In 2017, it amounted to 47,500 hectares. The volume of gross fiber production is only at the level of 40,000 tons per year, with a demand of 130,000 tons. The reduction in area is primarily due to the high cost of production – 2.5 times higher than other grain crops (Rozhmina *et al.,* 2018).

The oilseed flax can be an additional source of fibrous raw materials, with the area steadily growing and today amounts to more than 700,000 hectares (Federal State Statistics Service. 2019). Such rapid growth is associated with increased demand for seeds of valuable nutritional and therapeutic properties, sufficient specialized equipment, high technological efficiency, and profitability (Novikov *et al*., 2017).

The efficient use of oilseed flax in various sectors of the economy depends on both yield and quality indicators, which differ depending on the direction of the use of flax raw materials (Hasiewicz-Derkacz *et al*., 2015; Belopuhov *et al*., 2017; Moudood *et al*., 2019). The main deterrent to using its fiber is increased sharpness. For use in the textile industry, fine thread and high spinning ability are necessary, which largely depends on the length of the elementary fibers, where the higher the value of this indicator, the lower the breakage of the yarn (Ryzhova *et al*., 2011; Dmitriev *et al*., 2018). The pertinent study aimed to determine the optimum dosage of mineral fertilizers and methods of soil processing and preparation for successful flax (*Linum usitatissimum* L.) cultivation in the semi-arid conditions of the Almaty Region, Kazakhstan, focusing on achieving the highest seed yield with good quality.

MATERIALS AND METHODS

Experimental site and procedure

The flax (*Linum usitatissimum* L.) field experiment commenced at the Kazakh Research Institute of Agriculture and Crop Production, Almaty Region, Republic of Kazakhstan. The recent research focused on the oilseed flax cultivar Karabalykskaya. The experimental scheme involved the study of three levels of mineral fertilizers, i.e., N30P30K30, N60P60K30, and N90P90K30. Ammonium nitrate, ammophos, and potassium chloride became mineral fertilizers. The experiment also comprised three methods of plain tillage, i.e., shallow flat-cut tillage (10–12 cm depth), zero or no tillage, and conventional plowing (20–22 cm depth) designated as a control. Moldboard plowing progressed with a PN-4 plow, shallow flat-cutting cultivation with a KPG-250 flat-cutter, and spring harrowing with BZSS-1.0 harrows. The experiment ran on plots measuring 1100 m^2, with three repeats per treatment. The placement of experimental treatments followed a systematic arrangement (Dospekhov, 1985).

Weed control and crop treatment

The weed infestation assessment in the flax oil crop field continued during the herringbone phase when weeds were widespread. At this phase, applying a tank mixture of Samurai Super (540 g/ha) and Gerbitox (0.54 l/ha) to the flax crop helped control the weeds. Herbicide treatment throughout the growing season progressed using an ONSH-15 sprayer. Seed dressing involved the application of Tabu (0.9 l/t) mixed with the growth regulator Ecorost (2 l/t). Seeds' fungicide treatment engaged Mobitox.

Meteorological conditions

Weather data provided by the Kaskelen Meteorological Station, Almaty Region, Kazakhstan, indicated an average annual air temperature of 7.9 °C, with a sum of active temperatures amounting to 3800 °C. The yearly precipitation recording reached 244 mm, and the hydrothermal coefficient was 0.65. The growing season has spanned about 100–120 days. However, during the crop season study, the air temperature was significantly higher than the long-term average. Likewise, the growing season experienced extreme dryness, with only 141 mm of rainfall and a hydrothermal coefficient of 0.30. These conditions have characteristics of high temperatures and limited rainfall during the flowering-fruiting period, negatively impacting the seed setting of oil flax, leading to lower yields.

Soil characteristics

The presented research transpired on light chestnut, medium loamy soil. The soil characteristics were as follows: humus content (0–30 cm) ranged from 1.91% to 2.4% based on Tyurin's method, alkaline hydrolyzable nitrogen content according to Kornfield varied between 64–91 mg/kg, and mobile phosphorus and exchangeable potassium according to B.P. Machigin were in the range of 11–19 mg/kg and 230–275 mg/kg, respectively. The soil pH ranged from 7.9 to 8.4, with exchange bases total of 12–14 mg-eq/100 soil. Calcium was the predominant carbonate component, accounting for 12.0 mg-eq, while magnesium contributed less at 2.5 mg-eq. In the actual soil, the total N:P:K contents were 0.15%, 0.21%, and 1.67%, respectively.

Agrochemical analysis

The conduct of agrochemical analysis continued in the Laboratory of Soil Science and Agro-Chemistry, using standard methods. The following parameters were determined, i.e., total humus and labile humus content using a photoelectrocolorimeter (GOST-26213-91), nitrate nitrogen content using a laboratory ionometer I-160 MI (GOST-29270-95), mobile phosphorus using a photoelectric photometer KFK-3 "ZOMZ" (GOST-26205-91), exchangeable potassium using a flame photometer PFP-7 (GOST-26205-91), soil composition density based on A.N. Kachinsky's method, and structural-aggregate composition using a sieve analyzer. Moisture supply assessment followed A.F. Vadyunina and Z.M. Korchagina's approach.

Seed yield and its evaluation

The seed yield of oil flax's determination sustained threshing of the accounting area using a SAMPO-130 combine. Harvested seeds attained weighing, adjusting to 14% moisture content and 100% purity. The laboratory of technological evaluation of grains in plant samples had several quality indicators measured. Protein content detection used the Kjeldahl method (GOST 10846-91) and IK spectroscopy (FOSS), while fat content assessment employed the IK spectroscopy. The following guidelines ensured utilization during the study: Methodology of the state variety testing of agricultural crops (1972); Guidelines for the study of the world collection of oilseeds (1976); Guidelines for the determination of biochemical indicators of the quality of oil and seeds of oilseeds (1986).

Data analysis

All the recorded experimental data underwent mathematical analysis of variance using the method developed by Dospekhov (1984). Statistical analysis progressed using the STATISTIKA computer program, established by the Kazakh Research Institute of Agriculture and Plant Growing, Almaty Region, Kazakhstan.

RESULTS AND DISCUSSION

Before executing the experiment, initial testing of selected soil samples, after transfer to the laboratory, sustained chemical analysis. The results established the soil as initial fertility of light chestnut rainfed soil. According to the main phases of culture development, the selected soil samples exhibited the amount of total humus, nitrate nitrogen, mobile phosphorus, and exchangeable potassium during the growing season of the flax crop. The provision of the soil under the sowing of oilseed flax with mobile nutrients and humus state has gained validation. Recognizing the dynamics of productive moisture content in the soil pursued the application of different norms of mineral fertilizers and various tillage methods for oilseed flax. The influence of mineral fertilizers and tillage on the dynamics of physical properties during the growing season of the flax crop reached estimation. At the end of the oilseed flax growing season, the crop yield based on the various experimental variants was apparent. Past studies pointed out that in the conditions of the North Caucasus, with a low supply of soil with nutrients, the optimal fertilizer norm was N60P60K60, with an average of N30P30K30 or N30P30 (Sheudzhen *et al*., 2007; Bastaubayeva *et al*., 2023; Makenova *et al*., 2023).

The results indicated a trend toward a decrease in the total humus content in the soil at the end of the oil flax growing season, compared with the initial value before providing all different methods of soil processing and preparations, norms of mineral fertilizers, and planting the flax crop. At the same time, the total humus content in the soil against the background of N30P30K30 decreased more from plowing (0.09%), shallow flat-cutting (0.08%), and less with no treatment (0.06%) of the initial states. It was due to the intensive mineralization of humus with a small amount of fresh organic matter entering the soil during the cultivation of oil flax with a low rate of mineral fertilizers. After 13 years of zero treatment (Australia), in the 0–10 cm layer, the organic matter content was 3.13% with dump treatment (2.87%) (Gribanovsky, 2004).

Applying mineral fertilizers in the norm of N60P60K30 contributed to a slight decrease in total humus before harvesting oil flax compared with the initial content, and the trend for its decline remained in tillage; however, it was lowest in the zero tillage and shallow flat-cutting versus complete plowing. An insignificant decline in total humus content in the soil was evident when using mineral fertilizers with a norm of N90P90K30. However, the decrease during the growing season of the flax crop was 0.05% for plowing, 0.03% for shallow-flat tillage, and 0.02% for zero tillage of the initial quantities (Table 1). The zero technology is soil-saving, as confirmed by the data of experiments, where the average consumption of humus for a layer of 0–20 cm for four years with minimal technologies was 0.68%, while with annual plowing, it was equal to 2.5% (Korchagin *et al*., 2008).

The findings further signified that in all the variants of the experiments, there was an increase in nitrate nitrogen during the seedling phase of oil flax compared with its initial content in the soil before sowing the crop. The early spring precipitation and the prevailing moderate air temperature in April facilitated the resumption of the nitrification process in the ground. In the herringbone phase of oilseed flax, a decrease in nitrate nitrogen in the soil was noteworthy due to consumption by the cultivated crop. Oil flax experiences the greatest need for nitrogen in the interphase period between herringbone and the flowering stages. The introduction of nitrogen subcortex in the herringbone phase enhanced its amount in the soil by the flowering period with doses of N30, N60, and N90 on plowing by 20–22 cm, at 15, 19, and 29 mg/kg, respectively; flat-cutting by 10–12 cm at 12, 46, and 62 mg/kg, and without treatment at 10, 26, and 35 mg/kg, respectively. In the maturation phase of oil flax seeds, an increase in the content of nitrate nitrogen in the soil was distinct for all studied agricultural practices, from 26–73 to 36–91 mg/kg due to the lack of consumption and ongoing nitrification (Table 2). In Iran, Brazil, and Chile, using nitrogen at the rate of 100–150 kg/ha led to an increase in crop structure indicators and ensured a seed yield of 2.0–2.5 t/ha (Soethe *et al*., 2013).

Phosphorus accelerates the growth and development of flax plants, shortens the growing season, and increases the seed yield. By applying the phosphate fertilizers, the root system develops better, penetrates deeper into the soil, and branches out to the sides. The need for phosphorus was palpable throughout the growing season of the flax crop, especially during the period of shoots - the formation of 5–6 leaves, budding, and yellow ripeness. It is crucial for elements in an easily accessible

Table 1. Dynamics of the content of total humus (%) in light chestnut rainfed soil under oil flax when using different methods of basic treatment and application rates of mineral fertilizers.

Crop	Basic tillage methods	Norms of mineral fertilizers	Original content	Seed maturation phase
Oilseed flax grade Karabalykskaya	Plowing-20-22 cm	$N_{30}P_{30}K_{30}$	1.80	1.71
		$N_{60}P_{60}K_{30}$	1.76	1.68
		$N_{90}P_{90}K_{30}$	2.04	1.99
	Flat cutting -10-12 cm	$N_{30}P_{30}K_{30}$	2.,10	2.02
		$N_{60}P_{60}K_{30}$	2.07	2.01
		$N_{90}P_{90}K_{30}$	2.23	2.20
	Zero plowing	$N_{30}P_{30}K_{30}$	2.10	2.04
		$N_{60}P_{60}K_{30}$	2.,01	1.97
		$N_{90}P_{90}K_{30}$	2.07	2.05

Table 2. The content of nitrates (NO3) in oilseed flax crops, depending on mineral fertilizers and tillage techniques (mg/kg of soil, in a layer of 0–30 cm).

Crop	Basic tillage methods	Norms of mineral fertilizers	Original content	Phase shoots	Herringbone phase	Flowering phase	The phase of full maturation of seeds
Flax oil grade Karabalykskaya	Plowing-20-22 cm	$N_{30}P_{30}K_{30}$	19	25	10	25	37
		$N_{60}P_{60}K_{30}$	15	25	19	38	47
		$N_{90}P_{90}K_{30}$	17	24	18	47	61
	Flat-cutting-10-12 cm	$N_{30}P_{30}K_{30}$	17	36	14	26	36
		$N_{60}P_{60}K_{30}$	16	33	21	67	80
		$N_{90}P_{90}K_{30}$	17	30	11	73	91
	Zero plowing	$N_{30}P_{30}K_{30}$	14	34	18	28	39
		$N_{60}P_{60}K_{30}$	11	30	10	36	54
		$N_{90}P_{90}K_{30}$	13	39	22	57	70

form since the lack of an aggregate leads to a decline in seed yield, which attains no compensation by additional fertilization in top dressing at a later stage of the crop growing season. Phosphorus fertilizers for oilseed flax have recommendations for application, from 45 to 90 kg d.v./ha, depending on its content in the soil (Kolomeichenko, 2007).

Introducing phosphorus fertilizers in the norms of P30, P60, and P90 during sowing oil flax increased the content of mobile phosphorus in the soil at the beginning of the crop's growth period on the studied tillage methods compared with the initial values, which varied from 58 to 92 mg/kg. At the same time, against the background of N30P30K30, its amount in the soil increased more when using flat-cut tillage (10–12 cm) by 29 mg/kg than with plowing (20–22 cm) by 24 mg/kg and zero tillage (15 mg/kg). Against the background of N60P60K30, the most favorable conditions for phosphorus nutrition of the crop again developed on flat-cut tillage compared with other tillage options, and the mobile phosphorus content in the soil increased by 37 mg/kg, totaling 72 mg/kg. Against the background of N90P90K30, its amount increased on plowing by 46 mg/kg, followed by shallow flat-cutting (43 mg/kg) and no tillage (34 mg/kg), reaching the maximum values, i.e., 75, 79, and 71 mg /kg, respectively. Subsequently, from the initial phase to the maturation phase of the oil flax crop, in all the variants, a decrease in the content of mobile phosphorus in the soil was evident, ranging from 50–72 to 32–58 mg/kg, associating with the intensive consumption of this element (Table 3). In the Moscow region on sod-podzolic soil in the experiments of Krol (2010), the average yield of flax of the oilseed variety Norlin was at the level of 1.0 t/ha. The composition and doses of mineral fertilizers of

Table 3. Dynamics of mobile phosphorus content in oilseed flax crops depending on mineral fertilizers and tillage techniques, (mg/kg of soil, in a layer of 0–30 cm).

Crop	Basic tillage methods	Norms of mineral fertilizers	Original content	Phase shoots	Herringbone phase	Flowering phase	The phase of full maturation of seeds
Flax oil grade Karabalykskaya	Plowing-20-22 cm	$N_{30}P_{30}K_{30}$	33	57	52	46	39
		$N_{60}P_{60}K_{30}$	35	67	62	56	49
		$N_{90}P_{90}K_{30}$	29	75	67	62	58
	Flat-cutting-10-12 cm	$N_{30}P_{30}K_{30}$	38	67	57	47	32
		$N_{60}P_{60}K_{30}$	35	72	63	54	37
		$N_{90}P_{90}K_{30}$	36	79	72	62	43
	Without tillage	$N_{30}P_{30}K_{30}$	40	55	50	43	38
		$N_{60}P_{60}K_{30}$	35	61	56	48	43
		$N_{90}P_{90}K_{30}$	37	71	60	55	49

oilseed flax depended on the availability of soils with available forms of nutrients, precursors, and planned yield. They believed that the most effective treatment was introducing a complete mineral fertilizer, but in some cases, only phosphorus or nitrogen fertilizer could be helpful.

Flax plants need potassium throughout the growing season, especially during the budding, flowering, and seed formation periods. Utilizing potassium fertilizers for oil flax increases the number of ammonifying and nitrifying bacteria that eventually improve the nitrogen nutrition of plants. Raising the mass and volume of roots, water content, and water-holding capacity of the aboveground helps the plants better tolerate drought, lodging, and diseases. Gapienko *et al*. (2009) reported that potash fertilizers are not necessary when the content of exchangeable potassium is more than 25 mg/100 g in the soil.

Initiating potassium chloride at the rate of K30 increased the content of exchangeable potassium in the soil from 167–338 mg/kg (initial stage) to 344–446 mg/kg (in the seedlings phase of oil flax). In soil, the maximum increase in its amount appeared when using plowing (121–213 mg/kg), followed by flat-cut tillage (87–113 mg/kg) and the lowest in the variant without tillage (35–71 mg/kg). From the phase of the herringbone, there was a tendency to reduce the exchangeable potassium content in the soil until the maturation phase of oil flax crops. In the herringbone phase, its highest amounts in the soil emerged during plowing (320–362 kg/ha) compared with flat-cutting and no-tillage. At the flowering stage, the most favorable conditions in flax plants for potassium nutrition were again noticeable during plowing, and by the end of the growing season, the content of exchangeable potassium in the soil during plowing and flat-cutting almost leveled off; however, exceeding the zero tillage (Table 4). In the chernozems of Western Siberia, the recommended dose of nitrogen-phosphorus (60:60 kg) fertilizers was useful for oilseed flax; however, with low potassium content in the soil, complete measures of mineral fertilizers required application (Loshkomoynikov *et al*., 2011).

At the beginning of the oilseed flax growing season, soil moisture reserves during the autumn-winter period fulfilled the moisture need. The results further revealed that using zero tillage, the productive moisture accumulation and preservation in the meter layer from the germination phase to the maturation phase of oil flax occurred more and longer than plowing (20–22 cm) and shallow flat-cutting (10–12 cm). It might be due to less evaporation from the soil surface due to stubble and plant residues from zero tillage and direct sowing. Using mineral fertilizers in different norms did not affect the accumulation and preservation of moisture in the soil during the flax growing season. In the herringbone phase, the content of productive moisture in the soil decreased due to precipitation decline; however, it remained and maintained at an excellent level. At the same time, the lowest moisture content of the ground was notable in

Table 4. Dynamics of the content of exchangeable potassium in oilseed flax crops depending on mineral fertilizers and tillage techniques, (mg/kg of soil, in a layer of 0–30 cm).

Crop	Basic tillage methods	Norms of mineral fertilizers	Original content	Phase shoots	Herringbone phase	Flowering phase	Seed maturation phase
Flax oil grade Karabalykskaya	Plowing 20-22 см	$N_{30}P_{30}K_{30}$	233	446	362	297	215
		$N_{60}P_{60}K_{30}$	167	365	356	337	265
		$N_{90}P_{90}K_{30}$	223	334	320	279	247
	Flat-cutting 10-12 см	$N_{30}P_{30}K_{30}$	263	376	291	248	218
		$N_{60}P_{60}K_{30}$	305	392	297	276	263
		$N_{90}P_{90}K_{30}$	338	428	307	269	250
	Without tillage	$N_{30}P_{30}K_{30}$	295	366	273	236	175
		$N_{60}P_{60}K_{30}$	295	345	228	222	186
		$N_{90}P_{90}K_{30}$	327	362	257	243	204

the variant with the use of flat-cut processing (148.7–160.0 mm). Over five years, productive moisture accumulation was more abundant in oilseed flax crops with direct sowing than the traditional sowing technology (Turin *et al*., 2023).

The need for water sharply arises during the period of intensive growth of the stem (20–25 mm per day), which coincides with the end of the herringbone phase and the transition to the budding stage. Oil flax requires the most water at the beginning of the budding period when flower tubercles are protruding. At this time, sufficient precipitation and uniform distribution are necessary for harvesting a good seed yield. With a lack of moisture during this period, branching decreases, the duration of the flowering phase declines, and pods with a smaller seed mass lead to a reduced oil content. The absence of precipitation and an increase in air temperature from the beginning to the flowering stages of oilseed flax led to a sharp decrease in the amount of productive moisture in the soil during plowing (20–22 cm) from a very good (161.4–173.4 mm) to a poor (62.4–76, 8 mm) state, and flat cut (10–12 cm), from a good (148.7–160.0 mm) to a poor (61.2–72.8 mm) level. According to the dispersion analysis, the share of productive moisture in the formation of oilseed flax ranged from 36.0% to 63.7%, while in straw yield, the range was 30.4% to 46.5% (Rudik, 2016).

With the variant without treatment, the contained moisture slightly changed from a very good (165.7–191.1 mm) to a good (150.8–159.7 mm) level. During the flowering and pod formation, oil flax has the highest need for water. The prolonged severe drought at the flowering phase to the seed maturation stage significantly affects the flax seed yield. By the end of the oilseed flax growing season, the moisture content of the soil on plowing and flat-cutting cultivation with the use of mineral fertilizers became very poor (48.2–53.6 and 52.9–58.6 mm, respectively) and poor (64.3–68.0 mm) in the variant with zero tillage (Table 5). By sowing oilseed flax, the content of productive moisture in a meter layer of soil in direct sowing technology was higher than plowing by 26 mm (Zhenchenko *et al*., 2019).

The oil flax yield has weather conditions and the use of mineral fertilizers largely influencing it. With the application of low norms of mineral fertilizers (N30P30K30), the flax cultivar Karabalykskaya showed the highest seed yield at shallow flat-cutting (0.350 t/ha), which also excelled the plowing by 0.01 t/ha and zero tillage by 0.110 t/ha. The increased nitrogen and phosphorus concentrations in the average norms (N60P60K30) also enhanced the crop yield with shallow flat tillage by 0.06 t/ha, followed by plowing (0.05 t/ha), and zero tillage (0.04 t/ha). The use of increased norms of nitrogen and phosphorus fertilizers (N90P90K30) did not lead to an increase in the yield of oil flax in the plowing and shallow flat-cutting options due to soil drought. In the variant without the specified fertilizer rate, the flax yield increased by 0.06 t/ha due to the moisture conservation in the soil (Table 6). In the past experiments

Table 5. Dynamics of productive moisture reserves (mm) in the soil layer 0–100 cm in oilseed flax crops, depending on mineral fertilizers and tillage techniques.

Crop	Basic tillage methods	Norms of mineral fertilizers	Phase shoots	Herringbone phase	Flowering phase	Seed maturation phase
Flax oil grade Karabalykskaya	Plowing 20-22 см	$N_{30}P_{30}K_{30}$	175.8	173.4	67.7	50.4
		$N_{60}P_{60}K_{30}$	173.6	168.7	76.8	53.6
		$N_{90}P_{90}K_{30}$	176.4	161.4	62.4	48.2
	Flat-cutting 10-12 см	$N_{30}P_{30}K_{30}$	164.2	148.7	72.8	52.9
		$N_{60}P_{60}K_{30}$	169.3	150.0	67.2	58.6
		$N_{90}P_{90}K_{30}$	167.8	160.0	61.2	55.7
	Without tillage	$N_{30}P_{30}K_{30}$	175.4	165.7	159.7	64.3
		$N_{60}P_{60}K_{30}$	176.2	171.5	158.9	68.0
		$N_{90}P_{90}K_{30}$	180.1	175.1	150.8	67.1

Table 6. The yield of flax of the oilseed cultivar Karabalykskaya when applying different norms of mineral fertilizers and methods of basic tillage (t/ha).

Crop	Tillage	Norms of mineral fertilizers	Yield, t/ha	Gain from control, t/ha
Oil flax, grade Karabalykskaya	Plowing 20-22 см	$N_{30}P_{30}K_{30}$ (control)	0.340	-
		$N_{60}P_{60}K_{30}$	0.390	0.050
		$N_{90}P_{90}K_{30}$	0.350	0.010
	Flat cutting 10-12 см	$N_{30}P_{30}K_{30}$ (control)	0.350	-
		$N_{60}P_{60}K_{30}$	0.410	0.060
		$N_{90}P_{90}K_{30}$	0.360	0.010
	Zero tillage	$N_{30}P_{30}K_{30}$ (control)	0.240	-
		$N_{60}P_{60}K_{30}$	0.280	0.040
		$N_{90}P_{90}K_{30}$	0.250	0.010
NSR05 (Factor A - tillage)			0.14	
NSR05 (Factor B - mineral fertilizers)			0.14	
NSR05 (Interaction of factors A and B)			0.24	

conducted in the Tver Region, the highest yield of flax seed (1.45 t/ha) manifested by applying mineral fertilizers at the rate of N45P60K90 (Sorokina, 2018).

CONCLUSIONS

Mineral fertilizers' application with enhanced rates significantly impacted the preservation of total humus in the soil during the maturation phase of the oil flax crop. Compared with the plowing tillage method, the variant without minimal treatment exhibited a reduction in humus content. Regarding nitrate nitrogen content in the soil, it increased in the light chestnut soil during the crop's early vegetation stage and later decreased during the herringbone phase. Applying phosphorus and potassium fertilizers increased mobile phosphorus and exchangeable potassium in the ground during the seedling phase of oil flax. The variant with zero tillage showed the best moisture content during the flowering and seed-ripening stages. In terms of seed yield, using mineral fertilizers (N60P60K30) enhanced the flax seed yield under severe drought conditions. The variant with shallow flat-cutting and fertilizer (N60P60K30) demonstrated the highest flax crop productivity.

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