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RESEARCH ARTICLE
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Optimizing Cultivator-Fertilizer Performance with Tractor-Mounted Configuration in Northern Kazakhstan

Anton Nikolaevich Kuvaev [1,*], Alexey Ivanovich Derepaskin [1], Ivan Vladimirovich Tokarev [1], Yurij Vladimirovich Polichshuk [1], Yurij Viktorovich Binyukov [1], Pavel Grigoryevich Ivanchenko [1], Viktor Stanislavovich Kukhar [2] and Alexander Viktorovich Semibalamut [1]

[1]Kostanay branch of «Scientific production center of agricultural engineering», LLP, Abay Ave., 34, 110000 Kostanay, Republic of Kazakhstan
[2]Ural State Agrarian University, Karl Liebknecht st., 42, Yekaterinburg 620075, Russia
*Corresponding author: kuvaevanthon@yandex.ru

ABSTRACT

One of the most promising configuration schemes for cultivator fertilizer involves a fertilizer hopper mounted directly to the tractor frame. This configuration reduces the energy cost of overcoming the traction resistance generated by the cultivator fertilizer and increases its field capacity. The aim of this study is to evaluate the efficiency of the developed cultivator fertilizer with a tractor with an effective engine power of 300hp under the soil and climatic conditions of the northern region of Kazakhstan. The main scientific achievement of this work is the identification of patterns of change in energy and operational indicators depending on the operating modes of the cultivator-fertilizer device with an attached tractor in the soil and climatic conditions of the northern region of Kazakhstan. Scientific methods such as physical modeling, analysis and synthesis were used in experimental research. Based on the criteria of maximum field capacity and minimum specific fuel consumption, the optimum operating speed for the cultivator fertilizer was 9km/h. At this operating speed, the specific fuel consumption was 9.4kg/ha and the field capacity was 5.7ha/h. The agronomic evaluation indicators (soil crumbling, stubble preservation, deviation of the actual depth from the specified value and uneven fertilizer distribution) ensure the qualitative execution of the technological process in accordance with the specified requirements when operating in the justified mode. Compared to the comparable model, the use of the new cultivator-fertilizer resulted in a positive economic effect, including a 22% reduction in direct costs and a 15% reduction in labor costs and specific fuel consumption. This study was designed to achieve this goal.

Keywords: Cultivator-fertilizer, Mineral fertilizers, Draft resistance, Speed.

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INTRODUCTION

Maintaining stable crop yields is impossible without the use of one of the key techniques of intensive agriculture, the application of mineral fertilizers, especially in the form of granules (Izydorczyk et al., 2022; Haroon et al., 2023).

Three main methods of fertilizer application are used in existing cultivation technologies; 1) Basal or pre-planting fertilization, 2) Starter fertilization, 3) Application after sowing or top dressing (Shoukat et al., 2024). A closer examination of the basal application of granulated phosphorus-containing mineral fertilizers is warranted, given the widespread phosphorus deficiency observed in the soils of northern Kazakhstan. This deficiency highlights the necessity of targeted fertilization strategies to enhance soil fertility and crop productivity in the region (Chernenok et al., 2014). Taking under the consideration of soil and climatic conditions, the application of the base dose of granular phosphorus-containing fertilizers is carried out by their continuous subsurface distribution (Kunanbayev et al., 2022). In order to maximize the positive effect of the applied fertilizers, it is recommended to carry out this technological operation in late August to early September on fallow fields, combined with mechanical subsurface cultivation and simultaneous application of mineral fertilizers.

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In addition to phosphorus deficiency, the soil and climatic characteristics of the northern region of Kazakhstan are as follows (Baisholanov et al., 2025).

- The predominance of soils with heavy mechanical composition (over 50% heavy clay soils and over 20% medium clay soils) and low humus content (less than 5%)
- Lack of moisture during the growing season;
- Flat terrain and a considerable number (over 70%) of windy days per year (5m/s or more).

The first and second factors, among others, contribute to intensive compaction of the soil layer, while the third factor increases the risk of wind erosion in the soil. The problem is that under the studied soil and climatic conditions, the use of the existing cultivator fertilizers does not ensure the quality performance of the technological process in accordance with the established agrotechnical requirements (Nukeshev et al., 2019).

The solution to the scientific and technical problems identified is to develop technical means adapted to the soil and climatic conditions of the northern region of Kazakhstan (Derepaskin et al., 2024). For example, the Kostanay branch of the "Scientific Production Center for Agricultural Engineering" has been working for several years on the development of cultivator fertilizers for the continuous underground application of granular mineral fertilizers, which are designed for use with powerful tractors and with both fixed and variable application rates (Fig. 1).

Fig. 1: Prototype of the cultivator-fertilizer; a) general view; b) view in operation.

The cultivator fertilizers were equipped with a pneumo-mechanical ejector system for individual fertilizer metering (the number of seeders corresponds to the number of tillage units). A roller metering device was used to meter the specified amount of fertilizer, and transport was ensured by an air flow generated by a fan. Soil cultivation and uniform distribution under the soil is carried out by flat-cutting working bodies with distribution devices in the subsoil area (Kuvaev et al., 2024). Compared to the existing models with arrow-shaped (Nukeshev et al., 2018) or chisel-shaped working bodies (Nukeshev et al., 2023) and the plows used for plowing with moldboards (Romanyuk et al., 2023), the flat-cutting working body provides high-quality cultivation of the soil with a hardness of up to 5MPa at a depth of 12-20cm, leaving at least 60% of plant and stubble residues on the field surface, which leads to crumbling of the soil by at least 60%.

The leveling of the field surface and the creation of a wind-resistant, ridged soil layer are achieved by a rolling base, which is particularly important for the treatment of soils susceptible to wind erosion (Benyukh et al., 2023).

By using an individual ejector metering system, the distributor heads required for group metering of seeds and fertilizers (Kumar et al., 2000; Lei et al., 2018) and the need for an expensive sealed high-pressure hopper could be eliminated (Yatskul et al., 2018).

Compared to a similar cultivator fertilizer equipped with a group metering system (Polichshuk et al., 2021), the considered cultivator fertilizers with an individual ejector metering system reduced the uneven distribution of fertilizer across the working width from 9.1% (Polichshuk et al., 2021) to 5.4-5.6% (Derepaskin et al., 2023).

Reducing the uneven distribution of fertilizers has both economic and environmental impacts (Shillito et al., 2009; Stone et al., 2010; Moulin et al., 2012). In particular, the uneven distribution of fertilizers on the treated area can lead to a decrease in crop yields compared to their potential and an increase in chemical pollution of the soil.

A stirrer was installed above the openings of the reel metering device to prevent fertilizers from caking and arching over the openings of the metering device inside the hopper. This stirrer is configured as a shaft with pins mounted along its length in mutually perpendicular planes, as compared to helical stirrers similar to those described by Nukeshev et al. (2017). This design is less energy-intensive because it avoids horizontal movement of the fertilizer mass inside the hopper during stirring.

The tests conducted on the cultivator-fertilizers showed that they ensured the quality execution of the technological process in accordance with the requirements of the current normative documentation (Derepaskin et al., 2023). A drawback of the considered cultivator-fertilizer design is that positioning the fertilizer hopper directly on the frame of the tillage unit increases the force with which the tillage working bodies press against the furrow bottom. As a result, according to Goryachkin's formula (Chinenova et al., 2017), the component of the cultivator-fertilizer draft resistance associated with pulling the implement through the soil layer increases. To more effectively utilize the tractor's traction capabilities and increase the operating speed of the cultivator-fertilizer, it is necessary to optimize its design configuration such that the tractor's drawbar power is only used to overcome the draft resistance created by the tillage unit.

In previous stages of research (Derepaskin et al., 2024), the configuration scheme of the cultivator-fertilizer that includes a fertilizer hopper mounted on the power unit and a trailed tillage unit was theoretically justified. Additionally, the optimal ratio between the working width of the cultivator-fertilizer and the volume of the fertilizer hopper was justified, with $0.3m^3$ of hopper volume per meter of working width. The working width is 6.2m, and the hopper volume is $1.87m^3$. The optimal operating speed of the cultivator-fertilizer was determined to be 8.5km/h. The specified parameters of the cultivator-fertilizer were justified for a tractor with an effective engine power of 300hp.

To experimentally evaluate the validity of the justified parameters and modes of operation, a prototype of the cultivator-fertilizer was designed and manufactured, as shown in Fig. 2.

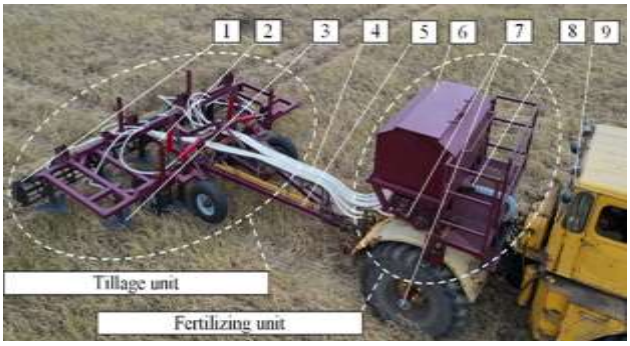

Fig. 2: General view of the cultivator-fertilizer with a mounted-trailed design; 1. Rolling basket; 2. Frame of the tillage unit of the cultivator-fertilizer; 3. Flat-cutting tillage working bodies; 4. Fertilizer tubes; 5. Tow hitch; 6.Fertilizer hopper; 7.Seeding unit with a drive mechanism; 8. Fan unit; 9. Tractor.

The cultivator fertilizer is designed for use with tractors with an effective engine power of 300hP on soils of different mechanical properties with a moisture content of the cultivated layer of 16-22% and a hardness of no more than 5MPa. The cultivator-fertilizer provided continuous soil cultivation and crumbling to a depth of 14-20cm and compaction of the surface layer with simultaneous subsurface application of granular mineral fertilizer at a dose of up to 150kg/ha. The aim of this work was to experimentally determine the optimal speed mode of the cultivator-fertilizer with a tractor having an effective engine power of 300hp. The main scientific accomplishment of this work is the identification of patterns of change in energy and operational-technological indicators depending on the operating modes of the cultivator-fertilizer with a mounted-trailed design in the soil and climatic conditions of the northern region of Kazakhstan.

MATERIALS & METHODS

Scientific methods such as physical modeling, analysis and synthesis were used in the study. This study was conducted in two phases. In the first phase, the rational speed of the device was determined. The optimization criteria were the maximum field capacity of the device and the minimum specific fuel consumption. In the second phase, a comparative economic evaluation was carried out between the developed cultivator-fertilizer model and the existing comparable model used in the northern region of Kazakhstan. Based on the results of the comparative economic evaluation, it was determined that the developed cultivator-fertilizer is effective under the considered soil and climatic conditions.

First Phase of Research

The plan for conducting the first phase of research on the cultivator fertilizer is presented in Table 1. This phase of the research was experimental and was conducted in the field. The cultivator-fertilizer was coupled with the tractor K-701 "Kirovets" with an effective engine power of 300hp.

The experimental studies were carried out under the most unfavorable conditions, when the fertilizer mass in the hopper was at its maximum (m_fr = 2300kg).

The variable parameter was the working speed of the cultivator-fertilizer (v = 7.0-10.0km/h, step 1.0km/h).

The operating speed of the cultivator-fertilizer, which ensured maximum field capacity and minimum specific fuel consumption while meeting the specified agrotechnical quality requirements, was recognized as rational. The quality of the technological process was assessed on the basis of the following indicators:

- Non-uniformity of fertilizer distribution along the working width of the cultivator-fertilizer working pass (%). Determined by GOST 28714-2007 (2008).
- Crumbling of the cultivated soil layer (%). Determined by GOST 33687-2015 (2016).
- Preservation of the stubble (%). Determined by GOST 33687-2015 (2016).
- Actual tillage depth (cm) and deviation of the actual tillage depth from the specified value (cm). Determined by GOST 33687-2015 (2016).

Before starting the experimental investigations with the cultivator-fertilizer, the characteristics of the field to be treated were determined according to GOST 20915-2011 (2013).

The engine crankshaft speed (RPM) was measured using the tractor's built-in tachometer. During the operation of the implement, it was ensured that the engine crankshaft speed was close to the nominal value (n = 1900±50 min-1) in all modes studied. The tractor was in good technical condition.

Table 1: The plan for conducting experimental studies

Evaluated parameter	Method for determining the parameter
Hourly fuel consumption, (G, kg/h)	Direct measurement
Draft resistance of the tillage unit of the cultivator-fertilizer, (R_{TIL}, N)	
Engine crankshaft RPM, (n, min^{-1}).	
Total draft resistance of the cultivator-fertilizer (R_d, N)	Calculation based on the obtained initial data
The power used to overcome the draft resistance of the tillage unit of the cultivator fertilizer (N_{TIL}, kW)	
Total power required to operate the cultivator-fertilizer (N_{total}, kW)	
Theoretical field capacity, (*C*, ha/h)	
Specific fuel consumption,(g_{sp}, kg/ha)	

The draft resistance of the tillage unit of the cultivator-fertilizer (R_TIL, N) at the corresponding speed was determined using the direct strain gauge method according to GOST 34631-2019 (2020).

The total draft resistance of the cultivator fertilizer (R_d, N) was determined using the following expression:

$$R_d = R_H + R_{TIL}, \tag{1}$$

where R_H is the draft resistance required to move a fully loaded fertilizer hopper, N.

The draft resistance required to move the fully loaded fertilizer hopper (R_H, N) was determined using the following formula:

$$R_H = (M_H + m_{fr}) \cdot \rho_{fr} \cdot g \cdot f_H, \tag{2}$$

where M_H is the structural (empty) mass of the fertilizing unit of the cultivator fertilizer mounted on the tractor frame (kg);
ρ_{fr} is the bulk density of granular mineral fertilizers (kg/m^3)
g – gravitational acceleration (m/s^2)
f_H = coefficient of rolling resistance of the tractor on the undisturbed soil layer.

The structural mass of the hopper (M_H, N) and the mass of the fertilizers (m_{fr}, kg) were determined by weighing, in accordance with GOST 26025-83 (1984). As shown in Fig. 3, the equipment used for strain gauging consisted of a spatial mechanism (Sarrus linkage) for fixing the S-shaped strain gauge element, a strain gauge station ZET 017-T8, a 100kN S-shaped strain gauge element with force-transmitting devices, shielded wires, and a personal computer.

Fig. 3: Strain gauge equipment used in experimental studies; 1. Personal computer; 2. Strain gauge system; 3. Force-transmitting devices; 4. Force sensor; 5. Shielded wire ; a) Exterior view of the strain gauge equipment; b) Components of the strain gauge equipment installed on the tractor's hitch system.

The power used to overcome the draft resistance of the tillage unit of the cultivator-fertilizer (N_{TIL}, kW) and to move the fully loaded hopper with fertilizers (N_H, kW) was determined using the following formulas:

$$N_{TIL} = R_{TIL} \cdot \frac{v}{3.6} \cdot 10^{-3} \tag{3}$$

$$N_H = R_H \cdot \frac{v}{3.6} \cdot 10^{-3}. \tag{4}$$

The total power used for operating the cultivator fertilizer (N_{total}, kW) represents the sum of the following components:

$$N_{total} = N_{TIL} + N_H + N_F, \tag{5}$$

where N_F is the power used to drive the fan unit from the hydraulic system of the tractor (kW).

The power consumed to drive the fan unit from the tractor's hydraulic system (N_F, kW) was determined according to the GOST 34631-2019 (2020) using the following formula:

$$N_F = \Delta p \cdot Q_{WF}, \tag{6}$$

where Δp –pressure drop between the inlet and outlet hydraulic lines, MPa;
Q_{WF} – flow rate of the working fluid, dm^3/s.

The pressures in the inlet and outlet hydraulic lines were determined using pressure gauges installed in the hydraulic system of the fan unit. The methodology used for determining was in accordance with GOST 34631-2019 (2020). Photographs of the pressure gauges installed in the hydraulic system of the tractor to assess the power used for the hydraulic drive of the fan unit are presented in Fig. 4.

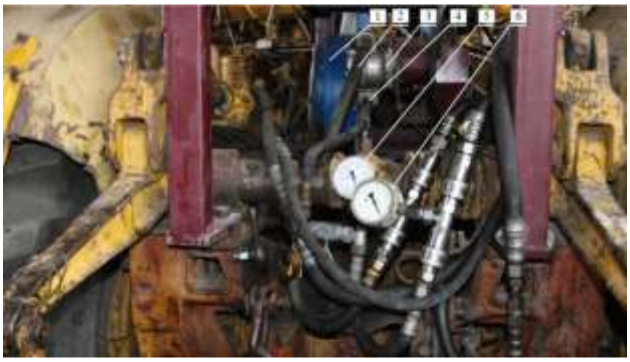

Fig. 4: Pressure gauges for measuring pressures on the inlet and outlet hydraulic lines of the fan drive hydraulic motor; 1 – fan unit; 2 – hydraulic motor inlet line; 3 – fan drive hydraulic motor; 4 – hydraulic motor outlet line; 5 – outlet line pressure gauge; 6 – inlet line pressure gauge.

The methodology for determining the theoretical field capacity (C, ha/h) follows GOST 24055-2016 (2017).

Specific fuel consumption (g_{sp}, kg/ha) was determined using the following formula:

$$g_{sp} = \frac{G}{C}, \tag{7}$$

where G – hourly fuel consumption, kg/h.

Hourly fuel consumption (G, kg/h) was determined using an IP-197 fuel flow meter. The discrete signals received from the flow meter were processed using IP-238 information and the measurement system. The methodology for measuring hourly fuel consumption was in accordance with the GOST 34631-2019 (2020). The fuel flow meter connected to the fuel system of the tractor is shown in Fig. 5.

Fig. 5: IP-197 fuel meter with IP-238 information-measurement system; 1 – fuel flow sensor; 2 – fuel meter electronic unit; 3 –accumulator battery; 4 – IP-238 information-measurement system; a) fuel flow sensors installed in the tractor's fuel system; b) fuel meter components installed in the tractor cabin.

Second Phase of Research

The initial data for the comparative economic evaluation were the results of the experimental studies on the cultivator fertilizer carried out in the first phase of the research. The economic efficiency of the developed cultivator fertilizer was evaluated based on the following indicators: savings in direct costs, savings in labor costs, savings in specific fuel consumption and the annual economic effect. The methodology for the comparative economic evaluation was in accordance with GOST 34393-2018 (2018).

RESULTS

Experimental studies of the prototype cultivator-fertilizer were conducted during the summer period (June-August) of 2024 in the Kostanay region. The soil hardness in the 10-20 cm layer was 5.3MPa, moisture was 20.6%, and density was 1.3g/cm^3. The soil conditions were typical for the northern region of Kazakhstan. A view of the cultivator-fertilizer prototype during the operation is presented in Fig. 6.

Fig. 6: The cultivator-fertilizer prototype coupled with the K-701 tractor while performing the technological process.

According to the weighing results conducted before the energy assessment, the structural mass of the fertilizing unit of the cultivator fertilizer was 1100kg and the tractor mass was 13640kg. The mass of the fertilizer in the hopper was 2300kg.

The results of the energy assessment of the cultivator-fertilizer prototype are presented in Table 2 and those of the operational assessment are presented in Table 3. The relative maximum measurement error was 4.1%.

As shown in Table 2, during the experimental studies, two modes of operation of the cultivator-fertilizer were observed: the normal operation mode (at the planned operating speed of v = [7.0; 9.0] km/h) and overload mode (at the planned operating speed of v = 10.0km/h). The tractor's traction capabilities ensured the change in the actual operating speed from v_{min} = 7.2km/h to v_{max} = 9.2km/h, which aligned with the planned speed modes of operation. Attempting to further increase the operating speed (up to 10km/h) was impossible for the following reasons:

1. An overload of the tractor's engine was observed owing to the increased draft resistance. The crankshaft RPM dropped significantly below the nominal value (n = 1800 min^{-1}). Prolonged operation of the engine in this mode is unacceptable, because it can lead to malfunction.
2. There was a significant increase in the slipping of the tractor wheels owing to the insufficient adhesion weight of the tractor. The wheel slip of the tractor prevented it from reaching the planned operating speed of 10km/h (the actual speed was 8.1km/h).

For the normal operation mode at an actual operating speed of v = [7.2;9.2] km/h, a monotonic increase in the draft resistance of the cultivator-fertilizer was observed. Thus, the increase in R_{TIL} (kN) and R_d (kN) for each 1km/h increase in speed were 4.7-5.5% and 4.5-5.3% respectively. An increase in draft resistance led to an increase in the power required to operate the cultivator-fertilizer. The increase in N_{total}(kW) for each 1km/h increase in speed was 14.1-21.9%.

In accordance with Table 3, during the unit's normal operation mode, an increase in operating speed of v = [7.2; 9.2] km/h led to a predictable increase in field capacity from C = 4.5ha/h to C = 5.7ha/h (an increase was 26.7%) and

Table 2: Results of the energy assessment of the cultivator-fertilizer

Speed (km/h)		Crankshaft RPM (min^{-1})	Draft Resistance R_{TIL}, kN	Total Draft R_d, kN	Tillage Power N_{TIL}, kW	Total Power N_{total}, kW
Planned	Actual					
7.0	7.2	1970	50.5	52.8	101.0	109.7
8.0	7.9	1940	52.9	55.2	116.1	125.233
9.0	9.2	1910	55.8	58.1	142.6	152.578
10.0	8.1	1800	53.3	55.6	119.9	129.2

Table 3: Results of the operational and technological assessment of the cultivator-fertilizer

Speed (km/h)		Crankshaft RPM (min^{-1})	Field Capacity (C) (ha/h)	Hourly Fuel Consumption (G) (kg/h)	*Specific Fuel Consumption* (g_{sp}) (kg/ha)
Planned	Actual				
7.0	7.2	1970	4.5	51.2	11.4
8.0	7.9	1940	4.9	53.2	10.9
9.0	9.2	1910	5.7	53.7	9.4
10.0	8.1	1820	5.0	50.3	10.1

a decrease in specific fuel consumption from g_{sp} = 11.4kg/ha to g_{sp} = 9.4kg/ha (a decrease was 17.5%). Hourly fuel consumption at v = [7.2; 9.2] km/h was within the range of G = [51.2;53.7] kg/h, which corresponds to the regulatory characteristic for this engine (Traction characteristics of agricultural tractors, 1979).

During the unit's overload operation mode (at the actual operating speed of v = 8.1km/h), the field capacity was C=5.0ha/h with a specific fuel consumption of g_{sp}=10.1kg/ha. Owing to the drop in crankshaft RPM below nominal levels, a certain decrease in hourly fuel consumption was observed: G =50.3kg/h. Therefore, based on the criterion of maximum field capacity and minimum specific fuel consumption, the optimal operating speed of the cultivator-fertilizer prototype with the K-701 «Kirovets» tractor was 9.0km/h. In the studied modes of operation, the crumbling of the processed layer was 66.2-68.4%, stubble preservation was 62.1-66.7%, the actual average tillage depth was 15.6-17.3cm (at a specified depth of 16cm), and the unevenness of fertilizer distribution was 6.1-6.9%. The actual values of the listed agrotechnical indicators aligned with the established agrotechnical requirements.

The results of the agrotechnical evaluation led to the conclusion that the values of the adopted and justified parameters of the cultivator-fertilizer ensure high-quality execution of the technological process in all the studied operating modes. In the comparative economic evaluation, a unit consisting of the K-730 «Kirovets» tractor (Kostanay Tractor Plant, 2025), a Ferti Box FB 3000 mounted fertilizer hopper (Bednar Ferti-box FB, 2025), and a Fenix FO 5003 cultivator (Bednar Fenix FO, 2025) was used for comparison. The working width of the comparable model is 5.3m, and the operating speed is 9km/h. The fertilizer application rate in all cases was 150kg/ha. The tillage depth was 15cm.

The results of the comparative economic evaluations are presented in Table 4. The initial data for the comparative economic evaluation are available in the online repository (https://zenodo.org/records/14907383).

Table 4: Indicators of the comparative economic efficiency of units based on comparable equipment models

Indicator	Indicator value for comparable equipment	
	Comparable model	New
Direct costs (euro/ha)	128	100
Labor costs(person-hours/ha)	0.283	0.242
Specific fuel consumption (kg/ha)	15.21	13.00
Annual economic effect (thousand €)	--	22.9
Capital investments (million €)	0.3	0.2

The economic evaluation carried out has shown that the use of the new cultivator-fertilizer prototype with a tractor that has an effective engine power of 300hp has a positive economic effect compared to a comparable implement, which is expressed as follows

- Direct costs fell by 22% from 128 to 100 euros/ha;
- Labor costs decreased by 15% from 0.28 to 0.24 person hours/ha;
- Specific fuel consumption fell by 15% from 15.2 to 13.0kg/ha.

The annual economic effect of using the developed cultivator fertilizer amounted to 22.9 thousand euros. Compared to the comparable units, capital investments decreased by 22.9%, from 300 thousand euros to 200 thousand euros. The structures of the direct costs for the compared equipment models are shown in Fig. 7.

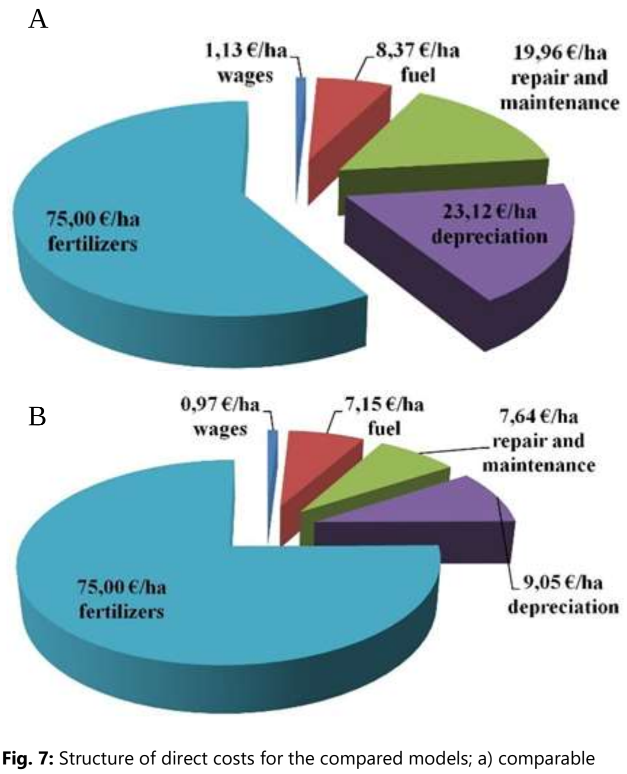

Fig. 7: Structure of direct costs for the compared models; a) comparable model; b) the cultivator-fertilizer under development.

DISCUSSION

The research presented in this paper focuses on the experimental justification of the optimal speed mode of operation for a cultivator-fertilizer under the soil and climatic conditions of the northern region of Kazakhstan (Aduov et al., 2023). The speed mode that ensures maximum capacity and minimum specific fuel consumption, while meeting the established agrotechnical requirements for treatment quality, was considered optimal. For a tractor with an effective engine power of 300hp, the optimal speed was determined to be v=9.0km/h. At this operating speed, the specific fuel consumption was found to be g_{sp}=9.4kg/ha, and the unit's field capacity was C=5.7ha/h. Under the justified speed mode, the total draft resistance of the cultivator-fertilizer was R_d=58.1kN. The results of the experimental studies are consistent with the theoretical studies conducted earlier (Derepaskin et al., 2024). The deviation between the theoretical value of the draft resistance and the experimental value falls within an acceptable range.

The soil hardness at a depth of 10–20cm during the experimental studies was 5.2MPa. According to the Medvedev classification (Medvedev, 2009), such soil is characterized as hard, making its qualitative processing challenging (Kuvaev, 2020a). Under these conditions, achieving soil crumbling of 66.2-68.4% and stubble retention of 62.1-66.7%, in alignment with agrotechnical requirements, was made possible by using a flat-cutting working body with a working width of 60cm and previously justified parameters (Kuvaev et al., 2024b). The ratio between the length of the chisel and the working width of the implement was sufficient to ensure both high-quality soil crumbling and residue conservation, which significantly distinguishes it from existing comparable models (Kuvaev, 2020b).

Our conclusion finds support in the research of Astafyev & Ivanchenko (2021), which established that subsurface tillage combined with stubble coulters provides maximum moisture reserves in the soil during the spring period. For this reason, the working body under consideration has been implemented in various designs of cultivators (Polichshuk et al., 2022) and cultivator-fertilizers. The actual average tillage depth ranged from 15.6 to 17.3cm (with the specified depth being 16cm), which complies with agrotechnical requirements. This was achieved due to the structural mass of the tillage unit of the cultivator-fertilizer being justified based on the most adverse soil conditions for operation (Derepaskin et al., 2022).

The implementation of the individual fertilizer dosing system that we developed (Tokarev, 2019) made it possible to achieve relatively low unevenness in fertilizer distribution across the working width of the cultivator-fertilizer, ranging from 6.1 to 6.9%. The results obtained align with the findings of previous experimental studies conducted on the considered system (Derepaskin et al., 2023). The preliminary results of the economic evaluation indicated that the cultivator-fertilizer under development will enhance the economic efficiency of the subsurface application of mineral fertilizers by reducing direct financial costs by 22%, labor costs by 15%, and specific fuel consumption by 15%.

The annual economic effect from using the cultivator-fertilizer under development, compared to the existing comparable model, amounted to €22.9 thousand, while capital investments decreased by 33.3%. This underscores the competitiveness of the cultivator-fertilizer being developed. The information presented above demonstrates that the development of a mounted-trailed cultivator-fertilizer represents a promising direction, which addresses the issue of equipping farms in the northern region of Kazakhstan with high-quality machinery for subsurface application of mineral fertilizers. In the next phase of research, the reliability of the design of the cultivator-fertilizer under development will be evaluated across various fields in the northern region of Kazakhstan.

Conclusion

Summarizing the results of the research carried out, we come to the following conclusion:

1. Based on the criterion of maximum field capacity and minimum specific fuel consumption, the rational operating speed for the cultivator-fertilizer is v=9.0 km/h. At this operating speed, the specific fuel consumption is g_sp=9.4 kg/ha and the field capacity of the machine is C=5.7 ha/h.
2. In the types of operation studied, the soil crumbling of the cultivated layer was 66.2-68.4%, the stubble conservation was 62.1-66.7%, the actual average cultivation depth was 15.6-17.3cm (at the specified depth of 16cm) and the non-uniformity of fertilizer distribution was 6.1-6.9%. The actual values of these agrotechnical indicators correspond to the specified agrotechnical requirements;
3. Compared to the comparable model, the use of the new cultivator fertilizer with a tractor with an effective engine power of 300hp enabled a 22% reduction in direct costs and a 15% reduction in labor costs and specific fuel consumption;
4. The annual economic effect of using the developed cultivator fertilizer amounted to 22.9 thousand euros. The objective of the research was achieved.

DECLARATIONS

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