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# JUSTIFICATION OF CULTIVATOR-FERTILISER CONFIGURATION SCHEME

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A possible way to increase the operating speed and field capacity of a cultivator-fertiliser is to modify its configuration scheme. According to our hypothesis, placing the fertiliser hopper directly on the tractor frame could reduce the traction resistance of the cultivator-fertiliser and consequently increase its operating speed and field capacity. Validating this hypothesis requires a comparative evaluation of the existing configuration schemes for cultivator-fertilisers. However, there are currently no such comprehensive studies available. This research aims to develop a mathematical model for conducting a comparative theoretical evaluation of various configuration schemes for cultivator-fertilisers. The development of this model incorporated principles from classical and agricultural mechanics. We developed a mathematical model and conducted a theoretical evaluation of existing configuration schemes for cultivator-fertilisers, such as mounting the hopper on a separate trailed chassis, mounting the hopper and tillage working bodies on one frame, and mounting the hopper directly on the tractor frame. The working width of the cultivator-fertiliser was constant and amounted to 6.2 m. The effective engine power of the tractor was taken to be $220 \times 10^3$ W. It was found that placing the fertiliser hopper on the tractor frame maximises the field capacity to 3.9 ha·h$^{-1}$. The increase in field capacity was 8.9–16.0%. In this case, the fertiliser hopper volume should be 1.89 m$^3$ and travel speed 8.45 km·h$^{-1}$.

**Keywords:** fertiliser hopper; tractive resistance; subsurface application; field capacity; working speed

Kazakhstan is currently the largest producer and exporter of grains in Central Asia (Scierhorn et al., 2020; Romanovska et al., 2023).

The majority of agricultural soils in northern Kazakhstan, where around 90% of all grains in Kazakhstan are cultivated, have low phosphorus availability (Tleubayev et al., 2021). In existing conditions, the most realistic approach to address the deficiency of this nutrient element is the utilisation of granulated phosphorus-containing mineral fertilisers, recognised as the most common and effective in agricultural production (Izydorczyk et al., 2022).

The maximum positive effect of their application can be achieved through subsurface application (Kunanbayev et al., 2022).

Due to the shortage of specialised cultivator-fertilisers, seed drills and seeding complexes are mainly used for this purpose (Nukeshev et al., 2019).

The shortage of specialised technical means is a scientific and technical problem, the solution of which is of great importance for the agricultural machinery industry in the northern region of Kazakhstan. For this reason, domestic researchers are conducting studies to develop the necessary technical means. These studies mainly focus on justifying the parameters and operating modes of individual units (Aduov et al., 2019; Nukeshev et al., 2017, 2023a; Tanabayev et al., 2023), seeding units (Nukeshev et al., 2016; Sugirbay et al., 2020), or working bodies (Nukeshev et al., 2018, 2023b, 2023c; Rustembayev et al., 2019; Sugirbay et al., 2023; Tanabayev et al., 2022). However, there are no studies dedicated to justifying the optimal configuration scheme of cultivator-fertilisers.

The analysis of scientific and technical literature and our patent research has shown that there are currently two most common configuration schemes of cultivator-fertilisers:

- a hopper, with a system for dosing and transporting mineral fertilisers has its own frame chassis and is attached to the tillage machine using a trailing method (Fig. 1a and 1b);
- a hopper, with a system for dosing and transporting mineral fertilisers is mounted on the frame of the tillage machine (Fig. 1c).

The cultivator-fertilisers made according to the first configuration scheme (Fig. 1a and 1b) by their fundamental structure are similar to wide-span seeding complexes (Agroinfo, 2024; Agristo, 2024; OEP, 2024).

For this scheme, there are two possible mutual arrangements of the tillage unit and the hopper:

- scheme 1a, the hopper mounted on the chassis is located in front of the tillage unit, in the direction of movement (Fig. 1a);
- scheme 1b, the hopper mounted on the chassis is located behind the tillage unit, in the direction of movement (Fig. 1b).

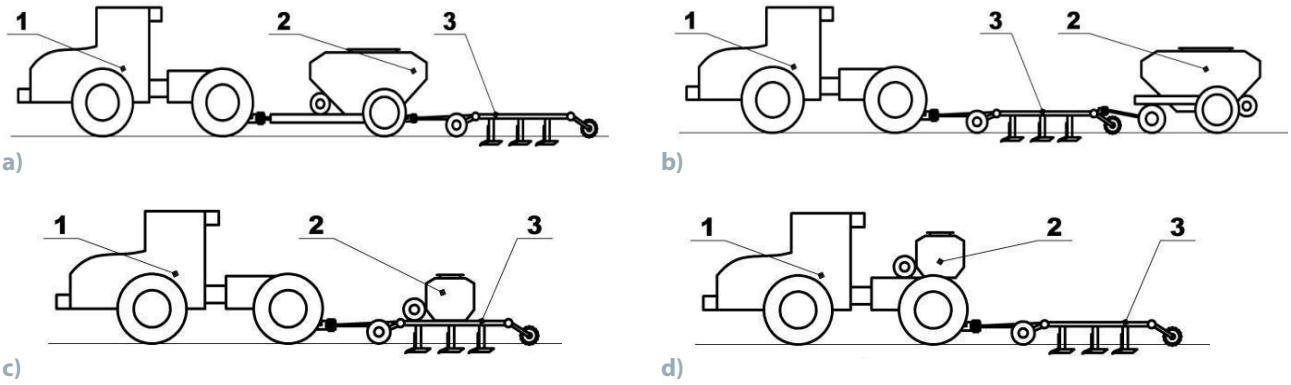


**Fig. 1** Variants of cultivator-fertiliser configuration schemes: a), b) a hopper is mounted on a separate trailed chassis; c) a hopper and tillage working bodies are mounted on the same frame; d) a hopper is mounted on the tractor frame
1 – tractor; 2 – fertiliser hopper; 3 – a frame with tillage working bodies

In the first case (scheme 1a), the chassis with the hopper mounted on it rolls over the undeformed soil layer, resulting in less force spent on its movement compared to a similar hopper from scheme 1b. At the same time, the location of the hopper behind the tillage unit (scheme 1b) provides better visibility and visual control of the entire machine. The main advantage of machines of this group is relatively high field capacity. This is achieved by reducing the number of fertiliser refills by using a trailed hopper with a large load capacity. The main disadvantages are, firstly, high unevenness in fertiliser distribution between the working bodies (no less than 20%), and secondly, a significant part of the power of the energy unit (up to 15%) is spent on rolling the fertiliser hopper over the field.

Uneven application of fertilisers deviates from agrotechnical requirements, leading to both an economic effect – a decrease in yield compared to the potential, and an environmental effect – an increased chemical load on the soil (Moulin et al., 2012; Nørremarket al., 2008).

The advantage of the second scheme (Fig. 1c) lies in its relatively simple design and high uniformity in the distribution of fertilisers among the working bodies (Quadro, 2024; Veles-Agro, 2024). The latter is achieved by using a system with an individual dosage for each working body.

One disadvantage of machines in this group is that placing the hopper directly on the frame of the tillage unit increases the force exerted by the tillage working bodies of the cultivator-fertiliser on the bottom of the furrow. Consequently, this leads to an increase in the tractive resistance of the cultivator-fertiliser, as it "drags" through the soil layer.

A possible solution is to place the hopper with the dosing and transportation system directly on the tractor frame (Fig. 1d). This will change the tractor's traction and power balance. In this case, the increase in power consumption for rolling the tractor will be compensated by reducing the power used to overcome the tractive resistance of the tillage unit of the cultivator-fertiliser. The released power "at the drawbar" of the tractor will increase the speed and the productivity of the machine. Additionally, uniform distribution of the load between the front and rear axles of the tractor allows for reducing wheel slippage, thereby decreasing soil compaction and enhancing its energy efficiency (Janulevičius and Damanauskas., 2015; Mohieddinne et al., 2023).

Similar studies are presented by Zhang et al. (2023). In this work, the authors achieved a more efficient utilisation of tractor's traction capabilities through the use of ballast weight.

Research on the functioning of a tractor as a traction and power unit was studied by Berezhnov (2007), Krasovskikh et al. (2015), Romanyuk et al. (2023), and others. In these works, the authors proposed mathematical models for determining the optimal configuration scheme for tillage and sowing units. However, these models do not take into account the mutual influence of the hopper's mass with the introduced material and the working width of the tillage unit on the changes in the machine's field capacity due to the varying number of refills. In addition, there are no studies that have evaluated the existing configuration schemes of fertiliser cultivators to identify the most effective one. Therefore, additional scientific research is needed to uncover the required patterns.

The aim of this research was to develop a mathematical model for conducting a comparative theoretical assessment of the various configuration schemes of cultivator-fertilisers. This model takes into account the influence of factors such as the fertiliser hopper's volume, the working width of the cultivator-fertiliser, and the number of refills on the machine's field capacity, which distinguishes this work from similar studies.

In turn, the consideration of a large number of factors enhances the reliability of theoretical research on justifying the optimal configuration scheme of cultivator-fertilisers.

The scientific novelty of this work lies in identifying the relationship between the configuration scheme of the cultivator-fertiliser and the optimal volume of the fertiliser hopper within this scheme, which ensures the maximum field capacity of the unit per work shift.

## Material and methods

The research methods are based on the concepts of classical and agricultural mechanics. Scientific methods such as mathematical modelling, abstraction, analysis, and synthesis were used in conducting the research.

The optimisation criterion of theoretical research was the field capacity per hour of shift time ($C_{SH}$, ha·h$^{-1}$), determined by the following formula:

$$C_{SH} = K_{SH\,(F=i)} \cdot C_T = 0.1 \cdot K_{SH\,(F=i)} \cdot W \cdot v \quad (1)$$

where: $K_{SH\ (F\ =\ i)}$ – utilisation coefficient of shift time, considering the number of fertiliser refills per shift $F = i$; $C_T$ – theoretical field capacity; $W$ – working width (m); $v$ – working speed (km·h$^{-1}$)

The utilisation coefficient of shift time $K_{SH\ (F\ =\ i)}$ characterises the ratio of the main (useful) work time ($T_M$, h) to the total shift time ($T_{SH}$, h):

$$K_{SH(F=i)} = \frac{T_M}{T_{SH}} \quad (2)$$

Each additional fertiliser refill for the cultivator-fertiliser requires the machine to stop, consequently reducing the main working time and the value of $K_{SH\ (F\ =\ i)}$. In this case, the value of $K_{SH\ (F\ =\ i)}$ for various numbers of refills can be determined by the following relationship:

$$K_{SH\,(F=i)} = I_{K_{SH\,(F=i)}} \cdot K_{SH\,(F=i)} \quad (3)$$

where: $K_{SH\ (F\ =\ i)}$ – utilisation coefficient of shift time, at the number of refills $F = i$

The working speed ($v$, km·h$^{-1}$) depends on two factors. Firstly, agrotechnical requirements determine the maximum permissible value of this indicator. Secondly, it is influenced by tractor's pull capabilities and the traction resistance of the cultivator-fertiliser.

The pull capabilities of the tractor ($P$, $N$) at the considered speed mode were determined according to the following dependence (Guskov et al., 1988):

$$P = \frac{N_e \cdot \eta_t \cdot \eta_u \cdot 3.6}{v} \quad (4)$$

where: $N_e$ – effective engine power of the power unit (W); $\eta_t$ – tractive efficiency of the tractor at the considered speed; $\eta_u$ – tractor traction reserve coefficient

The total tractive resistance of the cultivator-fertiliser ($R_S$, $N$) is the sum of the two terms:

$$R_S = R_H + R_{TIL} \quad (5)$$

where: $R_H$ – tractive resistance required to move a fully loaded hopper (N); $R_{TIL}$ – tractive resistance of the tillage part of the implement (N)

The tractive resistance required to move a fully loaded hopper ($R_H$, N) was determined according to the following dependence:

$$R_H = (M_H + V_{(F=i)} \cdot \rho_{fr}) \cdot g \cdot f_H \quad (6)$$

where: $M_H$ – structural mass of the hopper (empty) (kg); $V_{(F\ =\ i)}$ – fertiliser hopper volume at $i$-th number of refills per shift (m$^3$); $\rho_{fr}$ – fertiliser bulk density (kg·m$^{-3}$); $g$ – gravitational acceleration (m·s$^{-2}$); $f_H$ – coefficient of resistance to movement of the hopper over an undeformed or deformed soil layer

The volume of the fertiliser hopper ($V_{(F\ =\ i)}$, m$^3$) was determined according to the following expression:

$$V_{(F=i)} = \frac{0.1 \cdot K_{SH(F=i)} \cdot W \cdot v \cdot D \cdot T_F}{\rho_{fr}} \quad (7)$$

where: $D$ – dose of fertiliser application (kg·ha$^{-1}$); $T_F$ – time of continuous operation of the cultivator-fertiliser on a single fertiliser refill (h)

The tractive resistance of the tillage part of the cultivator-fertiliser ($R_{TIL}$, N) was determined using the rational Goryachk in formula (Chinenova, 2017):

$$R_{TIL} = W \cdot M_{sp} \cdot g \cdot f + W \cdot k \cdot h + W \cdot \rho_S \cdot h\,(0.28 \cdot v)^2 \quad (8)$$

where: $M_{sp}$ – actual specific mass of the implement (kg·m$^{-1}$); $f$ – coefficient of friction between soil and steel; $k$ – specific soil resistance (N·m$^{-2}$); $h$ – tilling depth (m); $\rho_S$ – soil density (kg·m$^{-3}$)

Considering Eq. (6) and (7), Eq. (5) will take the following form:

$$R_S = (M_H + V \cdot \rho_{fr}) \cdot g \cdot f_H + W \cdot M_{sp} \cdot g \cdot f + \\ + W_i \cdot k \cdot h + W_i \cdot \rho_s \cdot h\,(0.28 \cdot v)^2 \quad (9)$$

In order to determine the optimal working speed on the Cartesian coordinate system ($v$ (km·h$^{-1}$) – abscissa axis; $R_S$ (N) and $P$ (N) – ordinate axis), the graphs of the functions $R_S = f(v; V_{(F\ =\ i)})$ and $P = f(v)$ were plotted. The perpendicular line drawn from the intersection point of the graphs of the functions $R_S = f(v; V_{(F\ =\ i)})$ and $P = f(v)$ on the abscissa axis corresponds to the optimal speed mode of the cultivator-fertiliser. This speed will ensure the maximum utilisation of tractor's pull capabilities and the maximum possible field capacity of the cultivator-fertiliser with the considered configuration scheme and hopper volume.

The configuration scheme with the maximum value of $C_{SH}$ (ha·h$^{-1}$) was considered optimal for the cultivator-fertiliser coupled with the tractor under consideration.

**Table 1** Values of elements included in Eqs (1)–(9)

| Indicator | Indicator value |
|---|---|
| $N_e$ (W) | 220,000 |
| $W$ (m) | 6.2 |
| $\eta_u$ | 0.95 |
| $k$ (N·m$^{-2}$) | 30,670 |
| $h$ (m) | 0.16 |
| $M_{sp}$ (kg·m$^{-1}$) | 700 |
| $g$ (m·s$^{-2}$) | 9.81 |
| $\rho_S$ (kg·m$^{-3}$) | 1300 |
| $M_H$ (kg):<br>– for schemes 1a and 1b<br>– for schemes 2 and 3 | <br>3000<br>1100 |
| $\rho_{fr}$ (kg·m$^{-3}$) | 1250 |
| $f_H$:<br>– for scheme 1a<br>– for scheme 1b<br>– for scheme 2<br>– for scheme 3 | <br>0.09<br>0.13<br>0.30<br>0.07 |
| $T_{SH}$ (h) | 8 |

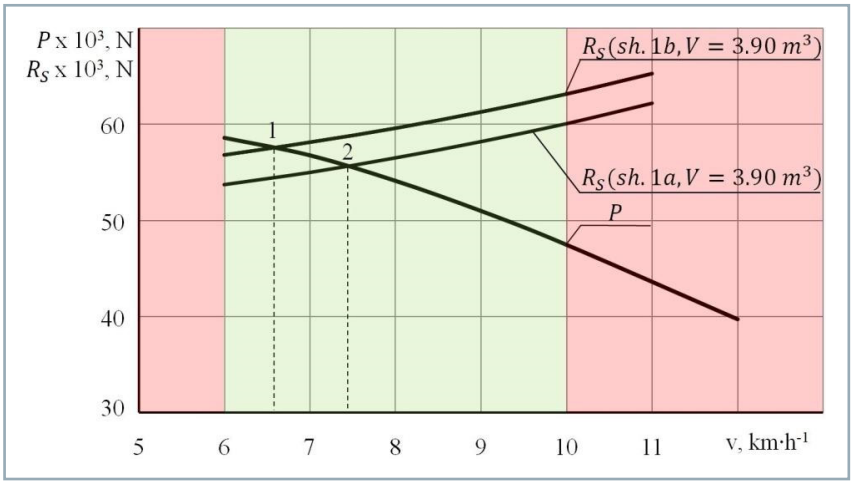


**Fig. 2** Influence of the location of the trailer chassis with fertiliser hopper and the speed of movement ($v$, km·h$^{-1}$) on the tractive resistance of the cultivator-fertiliser ($R_S$, N) with the hopper volume of $V_{(F=1)}$ = 3.90 m$^3$
configuration scheme 1

## Results and discussion

Agronomically permissible speed range for cultivation is 6–10 km·h$^{-1}$ (1.7–2.8 m·s$^{-1}$). The tractive efficiency of the tractor ($\eta_t$) depends on its speed and was determined by interpolating experimental data, presented by Astafiev et al. (2018) for the "Kirovets" K-744R1 ($N_e = 220 \cdot 10^3$ W).

The working width of the cultivator-fertiliser was constant and determined according to Kuvaev et al. (2021). For a tractor with an effective engine power of $22 \cdot 10^3$ W, the working width ($W$) was 6.2 m at a tilling depth of 16 cm.

The interpolated values of traction efficiency of the tractor "Kirovets" K-744R1 ($\eta_t$), as well as computational mathematical models used to establish the dependencies presented in this article are available in the online repository (Kuvaev, 2024). The values of the other elements included in Eqs (1)–(9) were constant and are presented in Table 1.

According to the results of timekeeping, conducted by us during the tests of various cultivators-fertilisers, the duration of one fertiliser refill of the machine is 15–20 minutes, which corresponds to approximately 4% of the total shift time of 8 hours. Consequently, each additional stop of the machine and its refilling with fertilisers reduces the $K_{SH}$ value by 4%. Dependence between the number of fertiliser refills, and the utilization coefficient of shift time and the volume of the fertiliser hopper is presented in Table 2.

In accordance with the developed research methodology, calculations were carried out and the graphs of

**Table 2** Dependence between the number of fertiliser refills, and the utilisation coefficient of shift time and the volume of the fertiliser hopper

| Number of refills per shift (F) | Utilization coefficient of shift time at $i$-th number of refills per one shift $K_{SH(F=i)}$ | Time of continuous operation of cultivator-fertiliser on single fertiliser refill $T_F$ (h) | Volume of fertiliser hopper $V_{(F=i)}$ (m$^3$) |
|---|---|---|---|
| 1 | 0.78 ($I_{K_{SH(F=1)}}$ = 1.00) | 8.0 | 3.90 |
| 2 | 0.75 ($I_{K_{SH(F=2)}}$ = 0.96) | 4.0 | 1.87 |
| 3 | 0.72 ($I_{K_{SH(F=3)}}$ = 0.92) | 2.7 | 1.21 |
| 4 | 0.69 ($I_{K_{SH(F=4)}}$ =0.88) | 2.0 | 0.86 |
| 5 | 0.66 ($I_{K_{SH(F=5)}}$ = 0.84) | 1.6 | 0.66 |

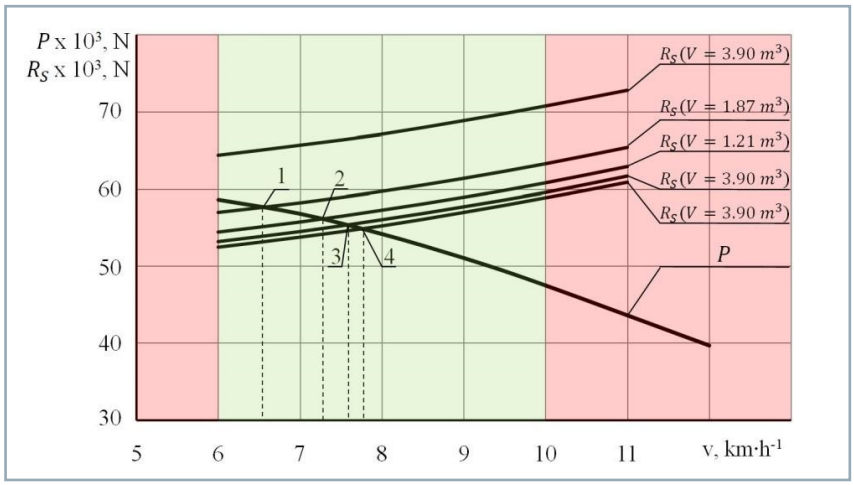


**Fig. 3** Influence of hopper volume ($V_{(F = i)}$, m$^3$) and speed ($v$, km·h$^{-1}$) on the total tractive resistance of the cultivator-fertiliser ($R_S$, N)
configuration scheme 2

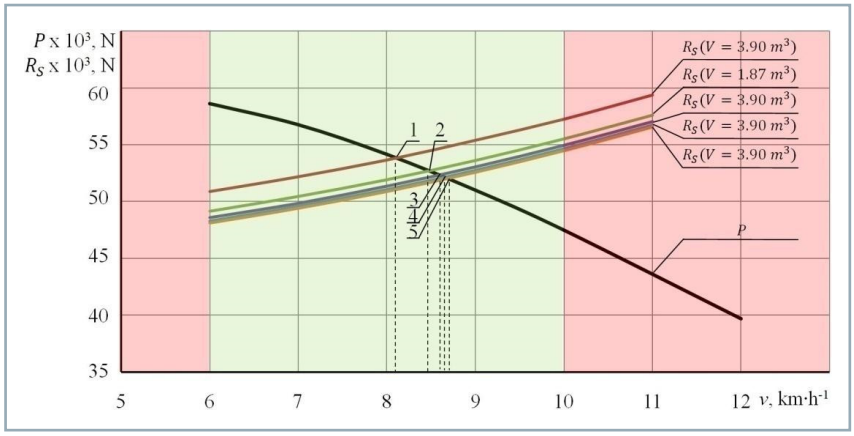


**Fig. 4** Influence of hopper volume ($V_{(F = i)}$, m$^3$) and speed ($v$, km·h$^{-1}$) on the total tractive resistance of the cultivator-fertiliser ($R_S$, N)
configuration scheme 3

**Table 3** Values of optimal speed ($v$, km·h$^{-1}$) and field capacity ($C_{SH}$, ha·h$^{-1}$) for considered configuration schemes

| Configuration scheme | Volume of fertilizer hopper $V_{(F = i)}$ (m$^3$) | Traction resistance $R_S$ (N) | Speed $v$ (km·h$^{-1}$) | Field capacity $C_{SH}$ (ha·h$^{-1}$) |
|---|---|---|---|---|
| **1a** | 3.90 (F = 1) | 57,510 | 7.40 | 3.58 |
| **1b** | 3.90 (F = 1) | 55,520 | 6.60 | 3.19 |
| **2** | 3.90 (F = 1) | – | – | – |
| **2** | 1.87 (F = 2) | 57,610 | 6.60 | 3.07 |
| **2** | 1.21 (F = 3) | 56,120 | 7.40 | 3.30 |
| **2** | 0.86 (F = 4) | 55,320 | 7.60 | 3.25 |
| **2** | 0.66 (F = 5) | 54,840 | 7.80 | 3.19 |
| **3** | 3.90 (F = 1) | 53,820 | 8.10 | 3.90 |
| **3** | 1.87 (F = 2) | 52,700 | 8.45 | 3.93 |
| **3** | 1.21 (F = 3) | 52,320 | 8.60 | 3.83 |
| **3** | 0.86 (F = 4) | 52,170 | 8.65 | 3.70 |
| **3** | 0.66 (F = 5) | 52,020 | 8.70 | 3.56 |

the functions $R_S = f(v)$ and $P = f(v)$ were plotted for the cultivator-fertiliser with various configuration schemes, as shown in Figs 2–4.

The optimal speed value ($v$, km·h$^{-1}$), corresponding traction resistance values ($R_S$, N), and field capacity values ($C_{SH}$, ha·h$^{-1}$) for the considered configuration schemes of the cultivator-fertiliser are presented in Table 3.

The analysis of the obtained results has shown that at the considered speed interval of 6–10 km·h$^{-1}$, depending on the configuration of the cultivator-fertiliser with a working width of 6.2 m, its operation with a tractor with an effective engine power of 220 · 10$^3$ W is possible under the following conditions:

– Schemes 1a and 1b (Fig. 1a, b). The hopper is mounted on a separate trailed chassis. According to Fig. 2 and Table 3, both variants considered are operable. The maximum field capacity for this configuration was $C_{SH}$ = 3.58 ha·h$^{-1}$ at a speed of $v$ = 7.40 km·h$^{-1}$ ($V_{H(F = 1)}$ = 3.90 m$^3$, the number of refills per shift – 1).
– Scheme 2 (Fig. 1c). The hopper is mounted on the tillage unit frame of the cultivator-fertiliser. In accordance with Fig. 3 and Table 2, the operation of the cultivator-fertiliser made according to this layout is possible with the hopper volume of no more than $V_{H(F = 2)}$ = 1.87 m$^3$ (the number of refills per shift – 2). At $V_{H(F = 1)}$ = 3.90 m$^3$ (the number of refills per shift – 1), the operation of the cultivator-fertiliser will be impossible because its tractive resistance will significantly exceed the pull capabilities of the tractor. This explains the lack of intersection points at the curves of functions $R_S$ ($V$ = 3.90 m$^3$) = $f(v)$, $P = f(v)$, and $P = f(v)$. The maximum field capacity for this configuration was $C_{SH}$ = 3.30 ha·h$^{-1}$ at a speed of $v$ = 7.40 km·h$^{-1}$ ($V_{T(F = 3)}$ = 1.21 m$^3$, the number of refills per shift – 3).
– Scheme 3. The hopper is mounted or hung on the tractor (Fig. 1d). In accordance with Fig. 4 and Table 3, the operation of the cultivator-fertiliser made according to this configuration scheme is possible with all considered hopper volumes. The maximum field capacity for this configuration was $C_{SH}$ = 3.93 ha·h$^{-1}$

at a speed of $v = 8.45$ km·h$^{-1}$ ($V_{T(F=2)} = 1.87$ m$^3$, the number of refills per shift – 2).

Among the considered configuration schemes of cultivator-fertilisers, scheme 3 (Fig. 1d) provides the maximum field capacity when operating with a tractor with an effective engine power of $220 \cdot 10^3$ W. Compared to configuration schemes 1 and 2, field capacity increased by 8.9–16.0%. We will use the obtained research results to design a cultivator-fertiliser for a tractor with an effective engine power of $220 \cdot 10^3$ W.

## Conclusion

1. A mathematical model was developed to conduct a comparative theoretical evaluation of various configuration schemes of cultivator-fertilisers, with the field capacity per hour of shift time as the optimisation criterion.
2. Configuration scheme 3, where the fertiliser hopper is mounted on the tractor frame, provides the maximum field capacity of $C_{SH} = 3.90$ ha·h$^{-1}$ when operated with a tractor with an effective engine power of $N_e = 220 \cdot 10^3$ W.
3. Compared to the most common configuration schemes, the increase in field capacity per shift was 8.9–16.0%.
4. To achieve the declared field capacity, the main parameters and the operational speed mode of the cultivator-fertiliser should have the following values: working width $W = 6.2$ m; fertiliser hopper volume $V_{(F=2)} = 1.87$ m$^3$; speed $v = 8.45$ km·h$^{-1}$.
5. The aim of the research has been achieved. The obtained research results will be used in the design of the cultivator-fertiliser to the tractor with an effective engine power $N_e = 220 \cdot 10^3$ W.

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