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JUSTIFICATION OF PARAMETERS OF A PRISMATIC DEVICE FOR FERTILISER DISTRIBUTION ACROSS THE WIDTH OF THE SUB-BLADE AREA OF A FLAT-CUTTING WORKING BODY

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Subsurface application of mineral fertilisers is an effective agricultural technique that improves both the quantity and quality of cultivated crops. To ensure uniform distribution of granular mineral fertilisers across the width of a tillage working body with a working width of 50 cm or more, spreading devices shaped like triangular prisms with curved working faces are installed in the sub-blade area. For uniform fertiliser distribution across the entire width of the sub-blade area, fertiliser particles must follow variable trajectories that evenly intersect the sub-blade area. Our hypothesis is that this can be achieved by modifying the spreading device, cutting off a portion so that the curved edges of its working faces have different lengths. The aim of this study is to determine the optimal angle of inclination of the cutting plane relative to the prismatic spreader's working faces. Our research methods include physical and mathematical modelling, as well as abstraction, analysis, and synthesis. We also conducted experimental studies in accordance with current regulatory documentation. The optimal angle of inclination of the spreader's cutting plane was determined to be 80°. We manufactured several spreader prototypes and conducted experimental studies to evaluate how the cutting plane's angle of inclination affects the unevenness of fertiliser distribution. The minimum unevenness, ranging from 24.5% to 27.8%, was achieved at a cutting plane angle of α = 75–80°. The graphical modelling method we developed accurately reflects the actual behaviour of the objects. Our hypothesis was proven valid, and the research aim was successfully achieved.

Keywords: mineral fertilizers; sub-blade area; subsurface application; distribution device; unevenness

One of the primary requirements for agricultural equipment used for applying mineral fertilisers, whether surface or subsurface, is the uniform distribution of fertiliser particles across the treated area. This is essential because failing to meet agrotechnical requirements for uniform distribution can lead to economic consequences, such as reduced crop yields, and environmental impacts, including increased chemical load on the soil (Shillito et al., 2009; Stone et al., 2010; Moulin et al., 2012).

Mineral fertilisers used in agriculture are available in both liquid (solutions and suspensions) and solid (primarily granular) forms. Although liquid fertilisers are more readily absorbed by plant roots, granular mineral fertilisers are more commonly used (Izydorczyk et al., 2022) due to the complexity of liquid application technology (Altieri and Cryer, 2018; Tanbayev et al., 2023).

This study focuses on granular phosphorus-containing fertilisers, as the soils in northern Kazakhstan, where at least 20 million tons of grain and leguminous crops are grown annually (Bureau of National Statistics, 2025), have low phosphorus availability (Chernenok and Barusky, 2014). The most significant positive effect from using granular mineral phosphorus fertilisers is achieved through subsurface application (Kunanbayev et al., 2022).

In mechanised subsurface application of mineral fertilisers, uniform distribution depends on two main factors:

- The uniform distribution of fertiliser particles among the tillage working bodies, which is influenced by the design, technological configuration, and parameters of the metering-transport system.
- The uniform distribution of fertiliser particles across the sub-blade area of the tillage body. To ensure uniform distribution across the working width of the tillage body's sub-blade area, spreading devices of various designs are installed.

This study focuses on the second factor: the devices responsible for distributing fertiliser across the width of the sub-blade area of the working body.

Spreading devices can be active (vibrating) or passive, the latter operating without an external drive. Passive devices are the most widely used. They operate without an external drive. They distribute material by changing the particles' trajectories upon contact with the spreader's surface. Although active vibrating spreaders (Xu et al., 2017; Zhu et al., 2025) ensure relatively high distribution uniformity, their complex design has limited their adoption for subsurface application.

Passive spreaders are classified into two groups based on particle trajectory:

- Spreaders where the particle trajectory forms an angle of α = 90° relative to the spreader's longitudinal-vertical axis of symmetry.
- Spreaders where the particle trajectory forms an angle of α = 0–180° relative to the spreader's longitudinal-vertical axis of symmetry.

The first group typically includes triangular prismatic spreaders with curved or straight working faces. When fertiliser particles interact with these faces, they move left or right relative to the working body's direction of movement. This ensures distribution occurs exclusively within the sub-blade area of the working body, minimising contact with the moving soil layer. However, a drawback is the higher unevenness of distribution compared to spherical or conical spreading devices.

The second group often consists of spherical or conical spreaders. With these, particles of the material, when interacting with the surface, can move left, right, forward, or backward relative to the direction of the working body's movement. In this case, fertiliser distribution across the width can occur both within the sub-blade area and partially beyond it. When wide tillage working bodies are used for subsurface application, the use of spherical or conical distribution devices is undesirable. This is because the risk of airborne fertiliser particles coming into contact with the moving soil layer increases, which, in turn, leads to greater unevenness in fertiliser distribution across the width of the sub-blade area.

The soils of northern Kazakhstan are prone to wind erosion due to the region's geography (Gendugov and Glazunov, 2007). Mechanical tillage without soil layer inversion is an effective way to reduce this risk. The flat-cutting working body is an effective tool for subsurface tillage, which has demonstrated its efficiency in the given soil and climatic region. Its main advantage is that it leaves enough residue on the surface (≥60%) to protect the soil from wind erosion (Sitting and Sur, 2024). For this reason, flat-cutting bodies are at least 50 cm wide.

When using a flat-cutting working body with a 50 cm working width for subsurface application of granular mineral fertilisers, a triangular prismatic spreader with curved working faces is the recommended choice for fertiliser distribution across the width of the sub-blade area. To ensure uniform distribution, the fertiliser particles must follow variable trajectories that evenly cross the plane of the sub-blade area across the working width. According to our hypothesis, this can be achieved by cutting off a part of the spreader so that the curved edges of the working faces have different lengths.

While previous studies have justified the parameters of prismatic, spherical, and conical passive spreaders (Artamonov, 2007; Nukeshev et al., 2020; Lopareva et al., 2021), providing new insights into subsurface distribution of seeds and fertilisers, no patterns have been identified between the length of the curved edge of the triangular prismatic spreader and the trajectory of the applied particles. This highlights the scientific novelty and relevance of this research.

The aim of this work is to determine the optimal angle of inclination of the cutting plane relative to the prismatic spreader's working faces.

Material and methods

The study was conducted in two stages. In the first stage, two-dimensional graphical modelling of the spreader was used to determine the theoretical value for the angle of inclination of the cutting plane, intersecting the working faces. In the second stage, experimental studies were conducted to verify the results from the first stage.

We used scientific methods such as physical and mathematical modelling, abstraction, analysis, and synthesis.

In addition, the experimental studies were based on the provisions of GOST 28714-2007 (2008).

During the graphical modelling, several assumptions were made:

- The kinetic energy of fertiliser particles at the moment they leave the working face of the spreader is sufficient to reach the farthest point of the sub-blade area.

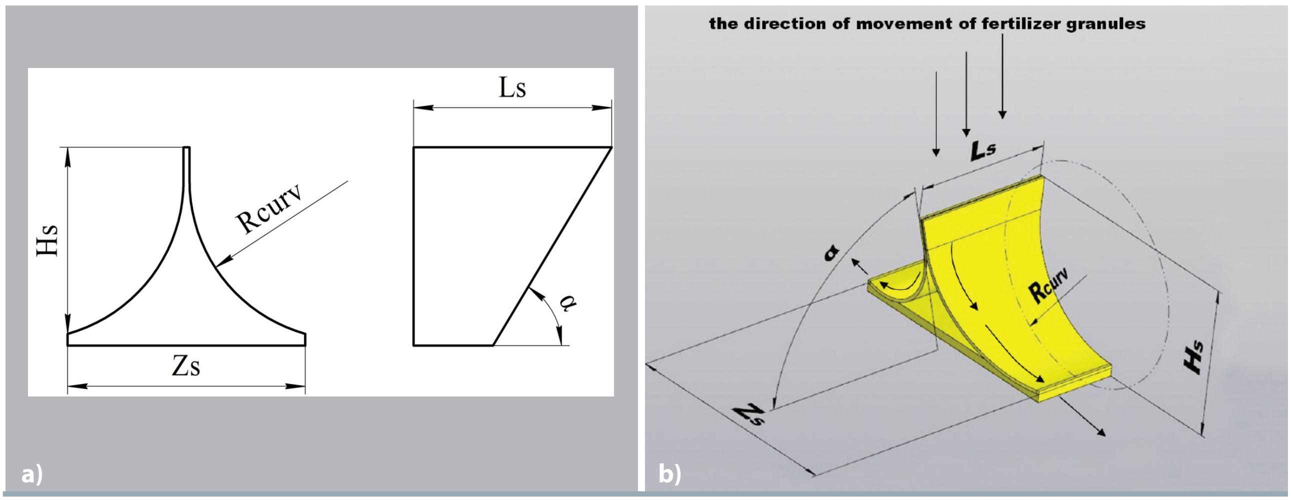


Fig. 1 Parameters of the spreader: a) 2D model of the spreader; b) 3D model of the spreader

– The impact of fertiliser particles on the spreader's surface is perfectly elastic.
– There are no collisions between fertiliser particles, or any rotation around their own axis.
– The following parameters were adopted for graphical modelling, based on studies conducted earlier (Fig. 1):
– The radius of curvature of the spreader's working faces RCURV = 35–40 mm;
– The height of the spreader HS = 50 mm;
– The width of the spreader's base ZS = 80 mm;
– The mounting height of the spreader above the furrow bottom h = 15–20 mm;

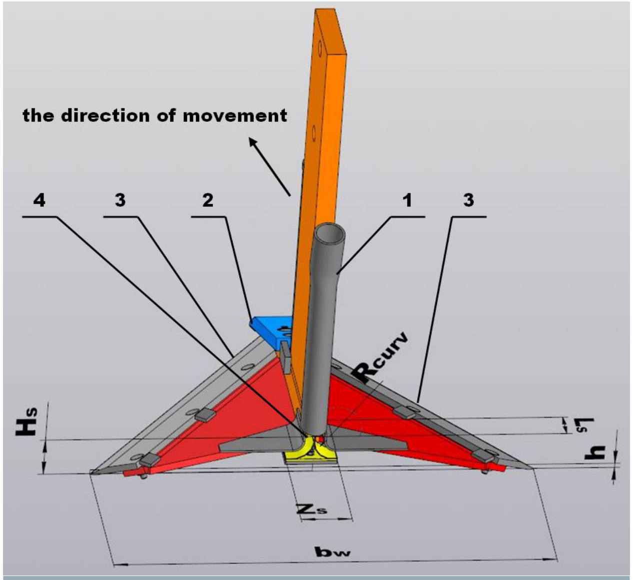


Fig. 2 The placement of the spreading device in the sub-blade area of the flat-cutting working body
1 – fertiliser tube; 2 – chisel; 3 – ploughshare; 4 – spreading device

– The length of the spreader LS = 35–40 mm;
– The width of the flat-cutting working body's sub-blade area bw = 500 mm.

The placement of the spreading device in the sub-blade area of the flat-cutting working body is shown in Fig. 2.

The technological process is as follows. The flat-cutting working body is securely attached to the frame of the tillage implement. The upper end of the fertiliser tube (1) is connected to a fertiliser supply system (not shown in the diagram), and the lower end is connected to the sub-blade area. During operation, the working body loosens the soil with the chisel (2) and ploughshares (3). Fertiliser flows into the tube (1), gains speed from the fan unit's airflow, and upon interacting with the spreading device (4) is distributed across the furrow bottom.

Since the selected model of the working body has a bilaterally symmetrical (mirror-symmetrical) design relative to its axis of symmetry, which passes through the shank, we consider only one half of it for graphical modelling.

To determine the angle of inclination of the cutting plane, the following construction was carried out (Fig. 3). The entire width of the sub-blade area was divided into ten sections of the same length. From each section, a tangent was drawn to the curve that forms the distribution surface. Through the points of tangency, straight lines were drawn onto the projection of the spreader, which was also divided into ten sections along its entire length. The intersections of these straight lines created points which, when connected, formed a curve. This curve established the desired angle α in relation to the horizontal plane.

To evaluate the effect of the cutting plane's angle of inclination on fertiliser distribution unevenness across the width of the sub-blade area of the flat-cutting working body, experimental studies were conducted. The plan for conducting experimental studies is detailed in Table 1.

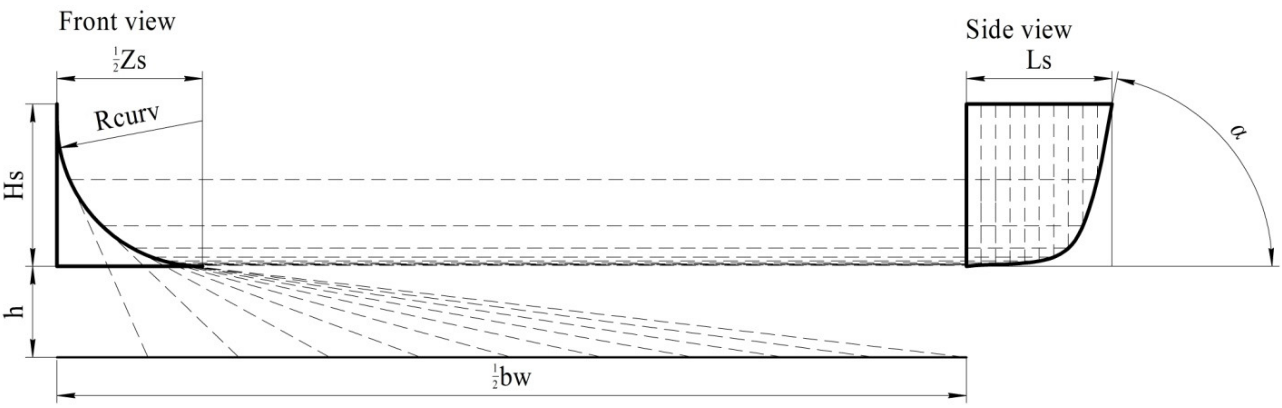


Fig. 3 Diagram for determining the angle of inclination of the cutting plane of the spreader

Table 1 The plan for conducting the experimental studies

Variable parameter	Evaluated parameter	Method for determining the parameter
angle of inclination of the spreader's cutting plane: 65–90° (step 6)	fertiliser mass in the *i*-th container (m_i, g)	direct measurement
	unevenness of fertiliser distribution between working bodies ($\upsilon_{(\alpha)}$, %)	calculation based on the obtained initial data

Total number of experiments is 40, with a 4-fold repetition

The sub-blade area of the flat-cutting working body was divided into 22 equal sections, each 3 cm wide. Each section corresponded to a container placed in the sub-blade area of the working body, as shown in Fig. 4b. Fertiliser was spread at a rate of 150 kg·ha^{-1}.

The optimisation criterion for the cutting plane angle of inclination was the unevenness of fertiliser distribution across the width of the sub-blade area. The optimal angle of inclination of the cutting plane was the one that resulted in the minimum unevenness.

The unevenness of fertiliser distribution across the width of the sub-blade area was calculated using the following formula:

$$\upsilon_{(\alpha)} = \frac{\sigma}{\bar{m}_{(\alpha)}} \cdot 100\% \tag{1}$$

where: $\upsilon_{(\alpha)}$ – unevenness of fertiliser distribution (%); σ – standard deviation of the mass of fertilisers in the container (g); $\bar{m}_{(\alpha)}$ – the arithmetic mean value of the mass of fertilisers in the container for a spreader with a cutting plane angle of inclination of $\alpha = 65–90°$ (g)

The standard deviation of the mass of fertilisers in the container was determined using the following formula:

$$\sigma_i = \sqrt{\frac{\sum_{i=1}^{n}\left(\Delta\bar{m}_{(\alpha)}\right)^2}{n-1}} \tag{2}$$

where: $\Delta\bar{m}_{(\alpha)}$ – deviation of the mass of fertilisers in the i-th container from the mean value for a spreader with a cutting plane angle of inclination of $\alpha = 65–90°$ (g); n – the number of cells

The fertiliser spreading and unevenness methodology followed GOST 28714-2007 (2008), and the methodology for processing the obtained experimental data was based on GOST R 8.736-2011 (2013).

This stage of the research was conducted using the laboratory-field setup and a version of the flat-cutting working body (Fig. 5). Different versions of the spreader, with varying cutting plane angles, were installed sequentially in the sub-blade area. The versions of the spreaders are shown in Fig. 6.

Fig. 5 Laboratory-field setup for subsurface application of granular mineral fertilisers with a variant of the flat-cutting working body
1 – fertiliser hopper; 2 – fertiliser metering device; 3 – fertiliser tube; 4 – flat-cutting working body; 5 – spreader

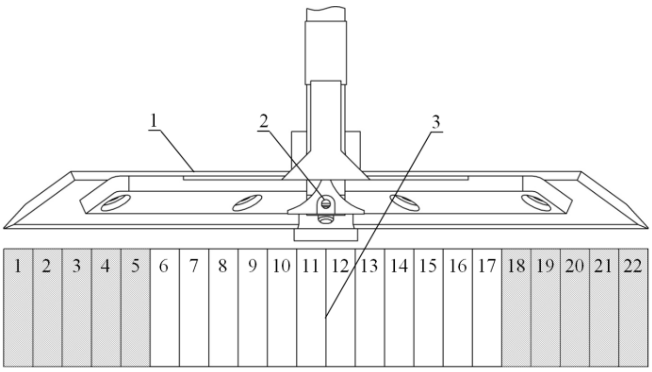
The fertiliser spreading time was 30 seconds. The airflow speed in the fertiliser tubes was 17–20 m·s^{-1}. The fertiliser mass in the containers was measured using CAS MWP-300H laboratory scales (with a stated measurement error of 2% according to the manufacturer's specifications).

The relative maximum measurement error was adopted as a quantitative characteristic of measurement accuracy. This measurement error ($\Delta_{\bar{X}(rel)}$, %) was determined as the sum of random and systematic errors:

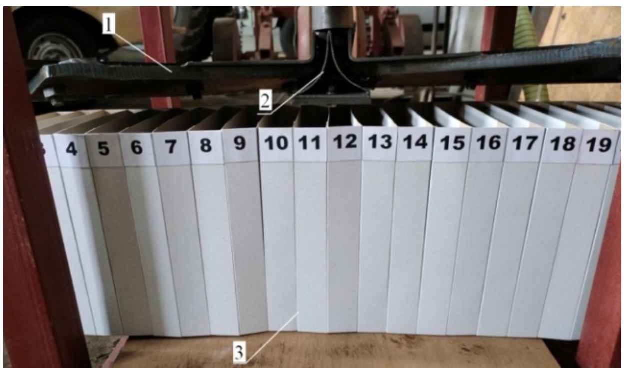
$$\Delta_{\bar{X}(rel)} = \Theta_{\bar{X}(rel)} + \Psi_{\bar{X}(rel)} \tag{3}$$

where: $\Theta_{\bar{X}(rel)}$ – relative systematic error (%); $\Psi_{\bar{X}(rel)}$ – relative random error (%)

The methodology for determining these values is in accordance with Novitsky and Zograf (1991).



a)



b)

Fig. 4 The relative position of the studied version of the flat-cutting working body and the containers for collecting fertilisers: a) diagram of the layout of sections in the sub-blade area; b) sub-blade area with containers installed for collecting fertilisers
1 – flat-cutting working body; 2 – fertiliser spreader; 3 – sections of the sub-blade area with their corresponding container

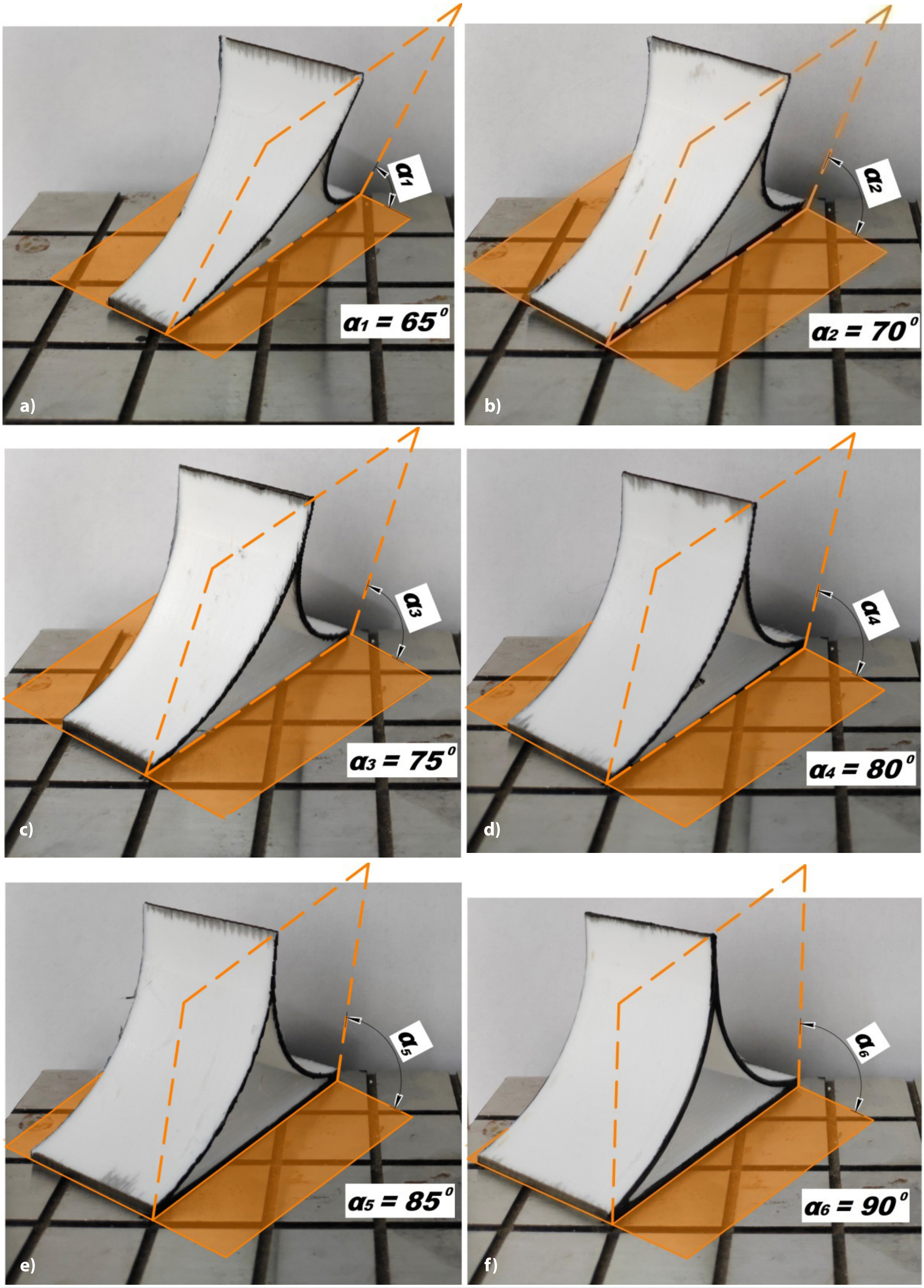


Fig. 6 Manufactured variants of the spreaders: a) $\alpha = 65°$; b) $\alpha = 70°$; c) $\alpha = 75°$; d) $\alpha = 80°$; e) $\alpha = 85°$; f) $\alpha = 90°$

Results and discussion

In accordance with the developed methodology (Fig. 3), graphical constructions were carried out to determine the angle of inclination of the spreader's cutting plane. The theoretical value for the angle of inclination α was determined to be 80°.

Next, in accordance with the plan for conducting experimental studies (Table 1), fertiliser spreading was carried out, and the obtained results were processed mathematically. The maximum value of the relative maximum measurement error was 7.1%.

The processed data, which were used to create the functional dependency graphs, are available in the online repository (Kuvaev, 2025).

Aa graph of the function $\upsilon_{(\alpha)} = f_{(\alpha)}$ was constructed in a Cartesian coordinate system (Fig. 7).

The analysis of the results showed a significant decrease in the unevenness of fertiliser distribution within the range α = 65–70°, from $\upsilon_{(65)}$ = 46.4% to $\upsilon_{(70)}$ = 34.5%. In the range α = 75–80°, the unevenness of fertiliser distribution across the width of the sub-blade area reached its minimum values: $\upsilon_{(75)}$ = 27.8% and $\upsilon_{(80)}$ = 24.5%. This range represents the optimum for the function. Further increases in the angle of inclination of the cutting plane led to a rise in the unevenness of fertiliser distribution across the width of the sub-blade area. Within the range α = 85–90°, unevenness was $\upsilon_{(85)}$ = 44.7% and $\upsilon_{(90)}$ = 57.5%.

To explain this pattern, the following steps were taken:

1. The sub-blade area of the flat-cutting working body was divided into three sections: a central section (corresponding to cells 9–14); an intermediate section (cells 6–8 and 15–17); and a peripheral section (cells 1–5 and 18–22), as shown in Fig. 4a.
2. An additional indicator was used to quantify the fertiliser concentration in each section of the sub-blade area, determined by the following formulas:

$$C_{C(\propto)} = \frac{\overline{m}_{C(\propto)}}{\overline{m}_{C(\propto)} + \overline{m}_{IN(\propto)} + \overline{m}_{PER(\propto)}} \cdot 100\% \tag{4}$$

$$C_{IN(\propto)} = \frac{\overline{m}_{IN(\propto)}}{\overline{m}_{C(\propto)} + \overline{m}_{IN(\propto)} + \overline{m}_{PER(\propto)}} \cdot 100\%$$

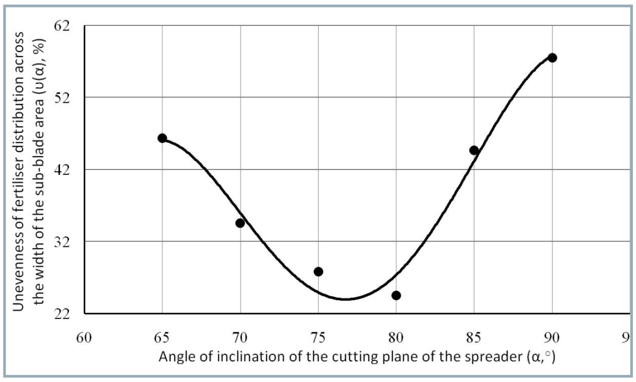


Fig. 7 Effect of the angle of inclination of the cutting plane of the distribution device (α, °) on the unevenness of fertiliser distribution across the width of the sub-blade area ($\upsilon_{(\alpha)}$, %)

$$C_{PER(\propto)} = \frac{\overline{m}_{PER(\propto)}}{\overline{m}_{C(\propto)} + \overline{m}_{IN(\propto)} + \overline{m}_{PER(\propto)}} \cdot 100\% \tag{6}$$

where: $C_{C(\propto)}$; $C_{IN(\propto)}$; $C_{PER(\propto)}$ – concentration of fertilisers in the central (cells 9–14), intermediate (cells 6–8 and 15–17), and peripheral (cells 1–5 and 18–22) sections of the sub-blade area of the flat-cutting-body, respectively, for a spreading device with a cutting plane angle of inclination of α = 65–90° (%); $\overline{m}_{C(\propto)}$; $\overline{m}_{IN(\propto)}$; $\overline{m}_{PER(\propto)}$ – the mean value of the fertiliser mass, respectively, in the central (cells 9–14), intermediate (cells 6–8 and 15–17), and peripheral (cells 1–5 and 18–22) sections of the sub-blade area of the flat-cutting working body for a distribution device with a cutting plane angle of inclination of α = 65–90° (%)

Values $\overline{m}_{C(\propto)}$; $\overline{m}_{IN(\propto)}$; $\overline{m}_{PER(\propto)}$; were determined according to the formulas:

$$\overline{m}_{C(\propto)} = \frac{\sum_{i=9}^{14} m_{i(\propto)}}{n_C} \tag{7}$$

$$\overline{m}_{IN(\propto)} = \frac{\sum_{i=6}^{8} m_{i(\propto)} + \sum_{i=15}^{17} m_{i(\propto)}}{n_{IN}} \tag{8}$$

$$\overline{m}_{PER(\propto)} = \frac{\sum_{i=1}^{5} m_{i(\propto)} + \sum_{i=18}^{22} m_{i(\propto)}}{n_{PER}} \tag{9}$$

where: n_C; n_{IN}; n_{PER} – the numbers of cells located under the central, intermediate, and peripheral parts of the sub-blade area of the flat-cutting working body, respectively

The results of these calculations are presented in Fig. 8. The initial data is available in the online repository (Kuvaev, 2025).

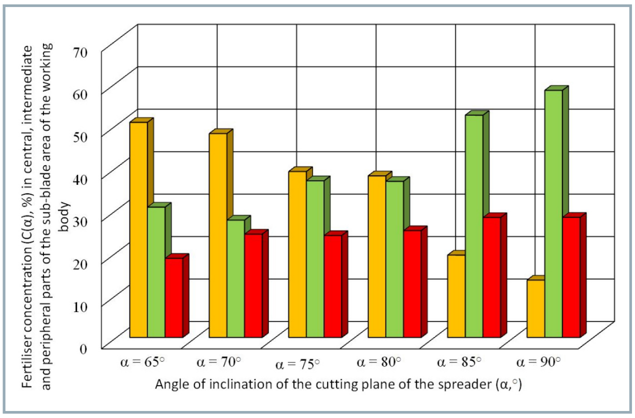


Fig. 8 The effect of the angle of inclination of the cutting plane of the spreader (α, °) on fertiliser concentration ($C(\alpha)$, %) in central, intermediate, and peripheral parts of the sub-blade area of the working body
■– central part of the sub-blade area; ■– intermediate part of the sub-blade area; ■ – peripheral part of the sub-blade area

According to Fig. 7, changing the cutting plane's angle of inclination in the range of α = 65– 90° in the sub-blade area of the flat-cutting working body affects fertiliser concentration as follows:

- In the range of α = 65–70°, an excessive concentration of fertilisers is observed in the central part of the sub-blade area ($C_{C(65)}$ = 50.7% and $C_{C(70)}$ = 48.0%) and insufficient in the intermediate ($C_{IN(65)}$ = 30.7% and $C_{IN(70)}$ = 27.6%) and peripheral parts ($C_{PER(65)}$ = 18.6% and $C_{PER(70)}$ = 24.3%).
- In the range of α = 75–80°, a more uniform concentration of fertilisers is observed across all sections of the sub-blade area ($C_{C(75)}$ = 39.1% and $C_{C(80)}$ = 38.1%; $C_{IN(75)}$ = 36.9% and $C_{IN(80)}$ = 36.8%; $C_{PER(75)}$ = 24.0% and $C_{PER(80)}$ = 25.2%).
- In the range of α = 85–90°, an excessive concentration of fertilisers is observed in the intermediate part of the sub-blade area ($C_{IN(85)}$ = 52.4% and $C_{IN(90)}$ = 58.2%) and insufficient in the central ($C_{C(65)}$ = 19.4% and $C_{C(70)}$ = 13.5%) and peripheral sections ($C_{PER(65)}$ = 28.6% and $C_{PER(70)}$ = 28.3%).

According to Fig. 6, reducing the cutting plane's angle of inclination also decreases the area of the spreader's working faces. This changes the fertiliser distribution pattern of across the width of the sub-blade area, affecting the concentration in the peripheral, intermediate, and central parts, and consequently, the unevenness of distribution.

It was concluded that for the prismatic spreader with the specified parameters (R_{CURV} = 35–40 mm, H_S = 50 mm, Z_S = 80 mm, h = 15–20 mm, L_S = 35–40 mm), the minimum unevenness in fertiliser distribution across the width of the sub-blade area ($\upsilon_{(75)}$ = 24.5% and $\upsilon_{(80)}$ = 27.8%) is achieved with a cutting plane angle of inclination of α = 75–80°.

Due to the relatively simple design and high efficiency, prism-shaped spreaders for uniform distribution of bulk materials in the sub-blade area of tillage working bodies have been widely used not only for subsurface fertiliser application but also for broadcast seeding of agricultural crops. For example, in the study by Anantachar et al. (2010), a group of researches utilised the computational capabilities of neural networks to justify the optimal parameters of a spreading device for broadcast seeding of peanut seeds. In the study by Radnaev et al. (2024), similar spreading devices were used for broadcast seeding of grain crops. In general, the theoretical foundation for justifying the parameters of prism-shaped spreading devices is based on classical collision theory (Awrejcewicz, 2012).

At the same time, the existing prism-shaped spreaders cause fertiliser distribution unevenness of 34–36% across the width of the sub-blade area (Loparev et al., 2021). The angle of inclination of the spreader's cutting plane (α = 75–80°), justified in our study, reduced distribution unevenness to 24.5–27.8%, which is at least 1.2 times lower.

Our studies confirm the hypothesis that uniform fertiliser distribution across the width of the sub-blade area can be achieved by cutting off a part of the spreader so that the curved edges of the working faces have different lengths. The research goal was accomplished.

The results of the studies have been used to design a new cultivator–fertiliser for subsurface application of granular mineral fertilisers (Derepaskin et al., 2024; Kuvaev et al., 2024).

Conclusion

We conducted a graphical modelling of the process of interaction between fertiliser granules and the spreader's working faces and determined the optimal angle of inclination of the cutting plane to be 80°.

We manufactured spreader prototypes and conducted experimental studies to evaluate the impact of the cutting plane's angle of inclination on the unevenness of fertilizer distribution across the width of the sub-blade area. The minimum unevenness, 24.5–27.8%, was achieved with a cutting plane angle of inclination α = 75–80°.

The graphical modelling method we developed for determining the cutting plane angle of inclination corresponds to the actual behaviour of objects. The research aim has been achieved.

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