International Journal of Technology 16(4) 1190-1208 (2025)

International Journal of Technology

http://ijtech.eng.ui.ac.id

Research Article

Substantiation of Distributor Parameters for Tiered Application of Mineral Fertilizer

Sayakhat Nukeshev [1], Mikalai Ramaniuk [2], Yerzhan Akhmetov [1], Kairat Eskhozhin [3], Khozhakeldi Tanbayev [4,*], Adilet Sugirbay [5], Shezhau Kadylet [6]

[1]*Department of Technical Mechanics, NCJSC S. Seifullin Kazakh AgroTechnical Research University, Zhenis Avenue 62, Astana 010011, Kazakhstan*
[2]*Department of Materials Mechanics and Machine Parts, Belarusian State Agrarian Technical University, 99/1, Nezavisimosti av, 220023, Minsk, Republic of Belarus*
[3]*Department of The Department of Agrarian Technique and Technology, NCJSC S. Seifullin Kazakh AgroTechnical Research University, Zhenis Avenue 62, Astana 010011, Kazakhstan*
[4]*Department of Engineering Technologies and Transport, Sh. Ualikhanov Kokshetau University, Abay st. 76, Kokshetau 020000, Kazakhstan*
[5]*Semey State University named after Shakarim, Research School of Veterinary Medicine and Agriculture, Semey, 071412, Glinka st, 20A, Kazakhstan*
[6]*Department of Technological Machines and Equipment, NCJSC S. Seifullin Kazakh AgroTechnical Research University, Zhenis Avenue 62, Astana 010011, Kazakhstan*
**Corresponding author:* khozhakeldi@shokan.edu.kz; *Tel.: +77071905101: Fax: 8(7162)255597*

Abstract: Intensive and extensive crop cultivation technologies are leading to the depletion of agricultural land fertility, causing a gradual decline in grain productivity. Soil fertility can be increased using mineral fertilizer, however it is necessary to consider the diversity in terms of space and depth as well as environmental aspects. Therefore, this study aimed to develop new design solutions by manufacturing machines for the intra-soil tiered application of fertilizer. The necessity in the development of such agricultural machinery was justified as the main mass of the wheat root system usually forms gradually at different depths (6 to 24 cm depth) and by the insufficient migration ability of phosphorus available for plant nutrition. Consequently, a distributor for the deep-loosener fertilizer unit had been designed, and important parameters were theoretically justified. During the analysis, the distributor flap installation angle β = 25–27°, the pipe installation angle α_1 = 47°, and pellet drop height h_1 = 53 cm. The proposed chisel-type working body with the distributor provided placement of differentiated doses of one/two types of fertilizer simultaneously at 3 different depths, at 8–10 cm (3rd pipe), 16–18 cm (2nd), and 23–25 cm (1st). In this process, 1st as well as 2nd pipes were in pairs, and 3rd pipe was separately regulated irrespective of the total cultivation depth, which allowed its application for any soil-climatic zones with different humus horizons. Field experiments have shown that the fertilizer distribution unevenness through the pipes 1 as well as 2 varies between 9 and 13%.

Keywords: Phosphorus fertilizer; Root system; Subsoil application; Tiered application; Variable-rate application

"This work was supported by the Science Committee of the Ministry of Science and Higher 621 Education of the Republic of Kazakhstan (Grant No. AP19674514)".

https://doi.org/10.14716/ijtech.v16i4.7648
Received February 2025; Revised March 2025; Accepted June 2025

1. Introduction

Climate is affecting plant growth rate, and any change in climatic parameters brings new opportunities or poses risks to agricultural land use (Ryan and Bristow, 2023; Abella et al., 2021). Soil degradation has become an increasing problem worldwide in recent decades. As a result, improving and maintaining the quality of degraded soil essentially depends on increasing the physical, chemical, as well as biological properties of the land (Rust et al., 2022; Liu et al., 2018; Ahmad et al., 2013). An estimation was conducted that nearly 2 billion hectares (ha) of soil resources in the world have been degraded, namely approximately 22% of the total cropland, pasture, forest, and woodland (Jie et al., 2002). Soil erosion is a crucial environmental problem, and assessment of its potential rate is useful in designing soil conservation strategies (Gunawan et al., 2013).

Most grain-growing territories in central and northern Kazakhstan covering 25.3 million ha are located in high risk farming regions, characterized by significant moisture deficit. The widespread ploughing of virgin and fallow lands has led to soil erosion and worsening water shortage. As a result, humus content declined by 40% from its original level, with hydrolysable nitrogen losses reaching 45–48%, and up to 57% under irrigation. Currently, agricultural land in Kazakhstan lose an estimated 0.5–1.4 tonnes/ha of humus annually (Mazhitova et al., 2023; Tanbayev et al., 2023; Saparov, 2013).

The main factors affecting soil fertility are violation of the agrotechnical requirements, scientifically based crop rotations, and the exclusion of fertilizer application in some cases (Sugirbay et al., 2023). There are certain disadvantages associated with the application of mineral and organic fertilizer in modern intensive technologies, including zero as well as minimum tillage (Fagodiya et al., 2024; Wardak et al., 2024; Nukeshev et al., 2023a; Mujiyo et al., 2022). In the technologies, fertilizer is spread on the soil surface without proper placement to the required depth, which does not contribute to the improvement and maintenance of soil fertility. This leads to greater as well as unstable consumption of fertilizer, reduces production efficiency, and harms both agricultural areas as well as the ecosystem.

The most effective method is the intra-soil application of fertilizer and ameliorants, where fertilizer is placed into the roots developing and moisture-rich layer of soil. This method decreases the fertilizer consumption, reduces the removal from sewage, and is easy to dose. Intra-soil application is also an environmentally friendly method of fertilization (Lishchuk et al., 2023; Saprykina, 2023; Tanbayev et al., 2022).

Soil nitrogen can be presented alone or as mineral and organic compounds. The use of organic fertilizer is limited by the treatment area sizes and insufficiency of the physical volume (Tang et al., 2024; Bai et al., 2023). Therefore, the main method of increasing the soil fertility of agricultural land is replenishment of soil nutrient reserves through the application of mineral fertilizer. Soils of grain-growing regions have a reserve in providing optimal nitrogen regime for plant nutrition due to the higher humus content in comparison with low humus soils and fallow fields. Consequently, the nitrogen regime of soils can be regulated by known technological methods (Zavalin et al., 2024; Zilio et al., 2023).

Phosphorus is an element limiting crop yields in its deficit (Wu et al., 2024; Wei et al., 2024; Qin et al., 2023). The replenishment of this element reserves and increasing the productivity of grain crops is possible only through the use of phosphorus mineral fertilizer (Li et al., 2023; Johnston et al., 2015). As a result, studies have established that the diversity of soil fertility indicators is observed in terms of area and diverse depth occurrence (Azevedo et al., 2018; Nukeshev et al., 2016). Proven low mobility of phosphorus compounds in the soil allowed the analysis to conclude that during the vegetative period, the spatial migration of the element does not exceed 1.0 cm. Despite 75 years of regular phosphorus fertilizer application at a certain site, there was no increase in its concentration in the deeper, illuvial soil layers (Sheujen et al., 2016). The outcome shows that phosphorus fertilizer remains at the depth at which it has been applied for a long time and may be inaccessible to plant root systems in case of non-compliance with the appropriate application depth

(Meyer et al., 2022). For the same reason, surface spreading of phosphate fertilizer is completely ineffective. Therefore, searching for technologies that ensure an effective and low-cost application of mineral fertilizer is necessary.

According to mechanical design features and root system peculiarities, the process can be supported by subsoiling or depth tillage treatments (Hobson et al., 2022; Houshyar and Esmailpour, 2018). Subsoiling is the most widely used and the quickest way to disturb hardpans as well as remove soil compaction (Khole et al., 2016). This process can improve soil structure, properties, promote the growth of plant roots, as well as the ability of crops to absorb nutrients and water from the soil (Akbarnia et al., 2018). Although there are several studies about the effectiveness of different types of soil tillers (chisel or subsoilers), the investigations are mostly not designed for fertilizer application (Song et al., 2022; Wang et al., 2022; Salar et al., 2021; Shmulevich et al., 2007). Existing implements are often used to apply fertiliser at the same level.

Based on the discussion, this study aims to substantiate the distributor parameters of the deep-loosener-fertilizer unit for deep tillage and tiered differentiated application of mineral fertilizer for grain crops. The design and technological scheme concerning the investigated distributor provides regulation of tiered depths in fertilizer application irrespective of the total depth of cultivation. The scheme also allows applying two types of fertilizer for any soil type and climatic zone with different humus horizons.

2. Materials and methods

2.1. Machine and implement design

Considering the absence of spatial migration of phosphorus available for plant nutrition and peculiarities of root system development of steppe varieties of wheat, there was a hypothesis that phosphorus fertilizer has to be applied intra-soil and at different depths (two or three layers). In this technology (Figure 1a), the first layer should be located at a depth of 8–10 cm, the second at 16–18 cm, and the third at 23–25 cm (Nukeshev, 2022; 2021). When the primary root system germinates due to the nutrient reserves of the seed, further development of roots is provided by first layer mineral fertilizers, thereby stimulating the formation of nodal roots and the friendly emergence of seedlings. Germinal roots, having received nutrition from the fertilizer on the first layer, sprout deep into the soil layer. During the process, fertilizer applied at a depth of 16–22 cm provided the formed root system with nutritional elements, allowing it to use the moisture reserves located in the lower soil horizons.

The deep loosener-fertilizer developed for the technology consisted of a frame, hitch, supporting, drive, and transport wheels (not shown in the figure as commonly known devices), two hoppers with sowing units, and 12 working bodies (Figure S1). The hopper was divided into two unequal rooms, one for nitrogen (or potash) and the other for phosphate fertilizer. Following the process, each room was equipped with a seeding unit with a fluted-roller spool, which was connected to the distributors (working bodies) by elastic pipes (Figure 1b).

The seeding units were driven from the drive wheels by chain gears and an infinitely variable gearbox (Amazone). This allowed the speed of the fertilizer seeding unit shafts to be varied, and the fertilizer was dosed from 0 to 400 kg per hectare depending on the position of the linear actuator. During the process, the linear actuator was connected to the fertilizer dose differential control and management system. The process allowed the fertilizer doses to be automatically changed according to the electronic prescription map in the adopted positioning system of the precision farming system.

After the process mentioned earlier, the metered fertilizer flowed to the crank unit, where the flow direction was turned by a certain angle before entering the distributor unit (a, b) as shown in Figure 2. The distributor unit was mounted flush on the rear edge of the inclined part of the working body, as shown in Figure 1. Additionally, the distributor unit in Figure 2 consisted of three metal pipes (1, 2, 3) with rectangular cross-sections attached one after another.

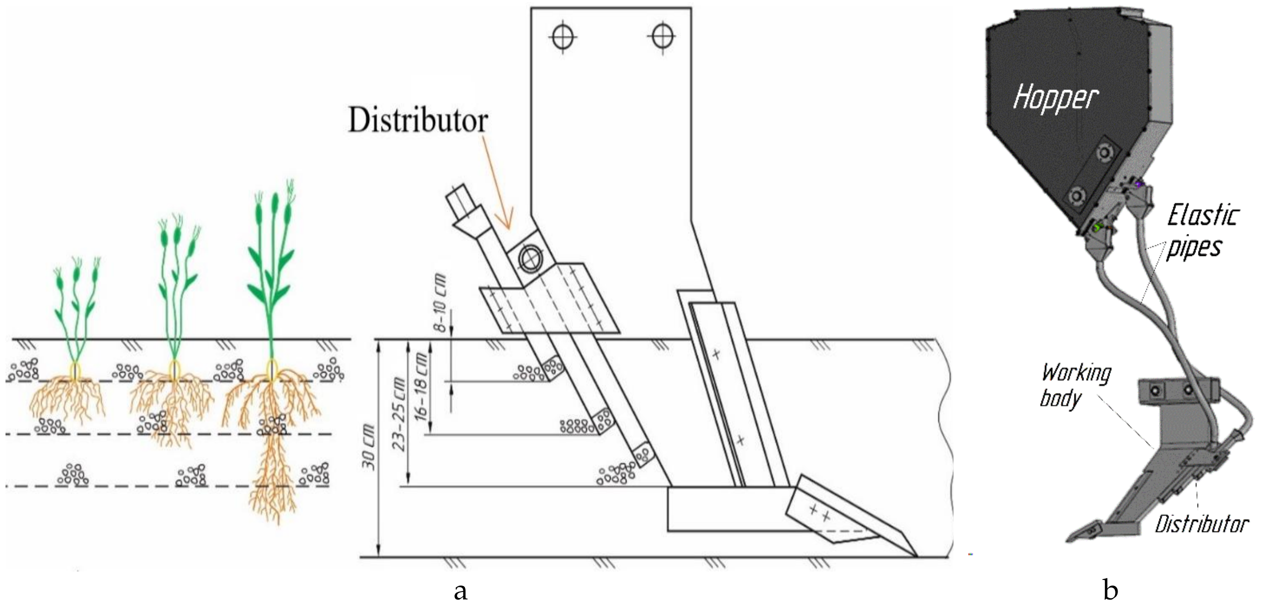

Figure 1 Technological scheme of tiered application of mineral fertilizer into the soil (a), 3D model of the working body with the distributor and hopper (b)

The first pipe (1) was designed to place phosphate fertilizer to a depth of 23–25 cm. Pipe (2) was also for phosphate fertilizer and placed at a shallower depth of 16–18 cm. Additionally, the third pipe (3) placed nitrogen (or potassium) fertilizer at a shallow depth of 6–8 cm.

The flow behavior of the fertilizer particles inside the distributor was theoretically studied using methods of classical and applied mechanics, as well as special sections of higher mathematics. During the analysis, the number of sown fertilizer granules between the pipes 1 and 2 was determined by experimental studies.

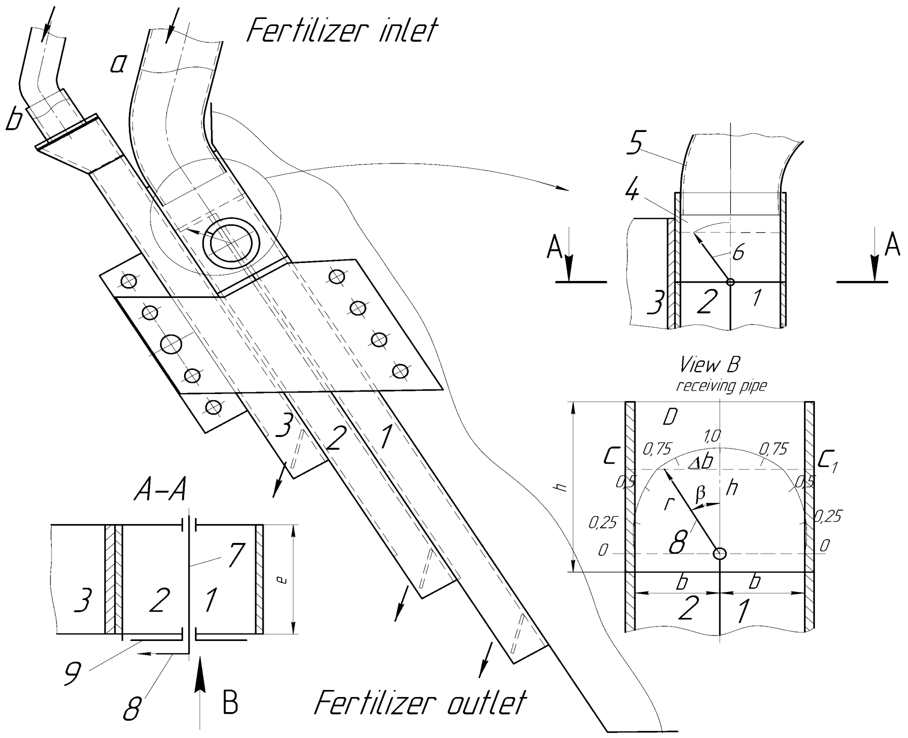

Figure 2 The distributor of the deep loosener-fertilizer 1, 2 – pipes for phosphate, 3 – pipe for nitrogen (or potassium), 4 – receiving pipe, 5 – fertilizer tube, 6 – flap, 7 – flap axis, 8 – indicating arrow, and 9 – dial

The sections were fixed rigidly to each other and could be adjusted relative to the stand using holes on it. The third pipe placed nitrogen, phosphate, or potassium fertilizer at a shallow depth of 6–8 cm and was connected to the sowing unit from the small compartment of the hopper by a separate pipeline.

The phosphate fertilizer flowed as a single stream up to metal pipes 1 and 2. The main task was to divide the current single flow into two preset doses, which were placed at different depths through the metal pipes 1 and 2. To divide the fertilizer flow at the upper border of the tubes, a flap was mounted on the axle, which was set at different angles β from the vertical axis of symmetry, ranging from 0° to $\beta/2$ to the left or right (Figure 2).

2.2. Experimental setup

For implementation of the proposed technology, an experimental installation was constructed, consisting of a mock-up sample of a hopper (1), a conveyor belt (2), and a working body (3) with the distributor (4) (Figure 4). Moreover, the outer known as the observable side of the pipes (5, 6), was made of organic glass for visual observation of the process of fertilizer flow division through pipes 1 (6) and 2 (5), as well as setting conditions of the flap (7).

Hopper (1) was filled with fertilizer, and the sowing fluted-roller spool driver was activated for the experiment. After the sowing mode was reached, special containers (9) were placed under pipes 1 as well as 2 and dosing continued for one minute. During the process, the dosed portions were weighed on a MW-II scale (8) with an accuracy of 0.01 g (Figure 3a), as repetition of each experiment was three times. Following this discussion, processing of the results consisted of determining the sowing amount through each pipe and establishing the dependence of the spreading quantity on distributor flap installation angle.

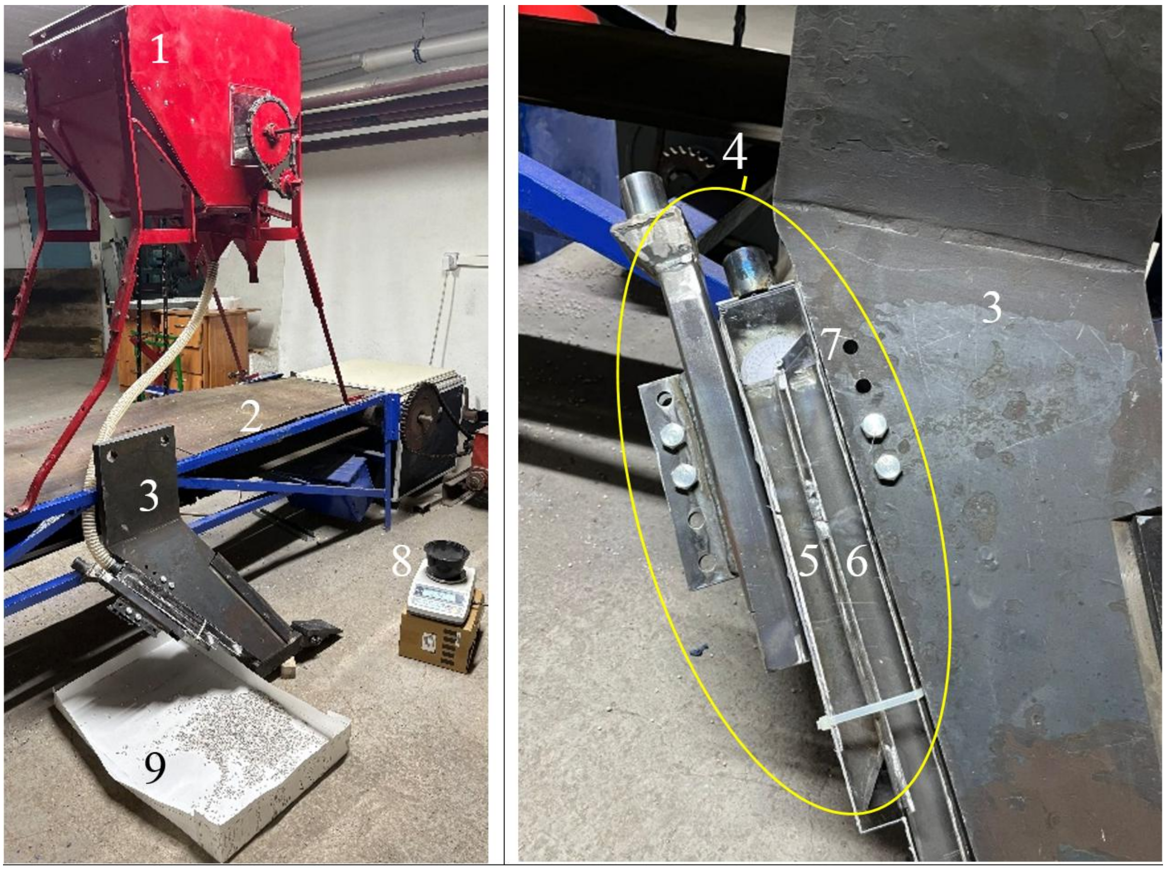

Figure 3 The experimental setup with the mockup sample of the working body and distributor, 1 – hopper, 2 – conveyor belt, 3 – working body, 4 – distributor (inside of yellow), 5 – pipe 2, 6 – pipe 1, 7 – flap, 8 – scale MW-II, 9 – container

Field experiments in this study were conducted in Tselinograd district of Akmola region, Kazakhstan. The soil type in the experimental area was dark chestnut, and the granulometric composition of the soil was medium loamy. In addition, the relief was flat without a slope, no stones, and had plant remains. Microrelief was associated with a homogeneous soil type, and the ridge was 4.2 cm. In the experimental plots, the soil layer (up to 35 cm) was moderately moist, and in the average horizon (5...15 cm), its humidity did not exceed 28.15%. The hardness of the soil was 1.1 MPa, and it was more compacted to 2.1 MPa in the stubble background. During the analysis, field tests of deep loosener-fertilizer were conducted in 2024 by aggregating with tractor Buhler versatile 2375 on autumn tillage (Figure S1) with simultaneous in-soil tiered application of mineral fertilizer following GOST 28714-2007 (standard). At the same time, the flap setting angle was adjusted for uniform distribution on pipes 1 and 2 in field conditions. To determine the unevenness of distribution between these pipes, the outermost working body was freed from fixing and set, allowing it to be above the soil during operation. Moreover, special bags for collecting the applied fertilizer were connected to the distributor outlets.

3. Results and Discussion

3.1. Theoretical studies

3.1.1. Determination of the fertilizer mass flowing through the cross-section of the fertilizer-pipe

The fertilizer flow on the way to the distribution unit met the cylindrical crank unit, where the bending axis of the pipe formed an angle-α (Figure 4). In this case, the lower part of the pipe was positioned vertically, while the upper part was angled at α relative to the vertical section. The behavior of bulk material passing through such a bending part was often of practical interest. Initial theoretical studies were based on the following hypothesis, namely, a quasi-homogeneous multiphase medium consisting of several components at a certain concentration and mutual penetration was obtained as a continuous medium.

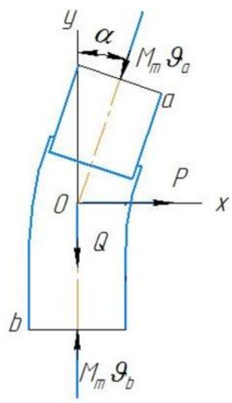

Figure 4 Flow of mineral fertilizer granules through cranked fertilizer pipe

a and b were pipe section boundaries, α - inclination angle of the cylindrical steam pipe, P – the main vector of surface forces, Q – the main vector of volumetric forces. $M_m\vartheta_{ax}$ and $M_m\vartheta_b$ – instantaneous quantities of particles motion in the corresponding bend.

The considered part of the bending pipe was between lines a as well as b, and the material in this part was in an equilibrium state as shown in Figure 4. This was favored by surface and volume forces, as well as the instantaneous quantity of motion of the material flowing through the considered part. Surface forces included the pipe wall reaction forces on the flow materials, and volumetric forces comprised the forces acting on all material particles, known as gravity.

According to Euler's theorem related to continuum mechanics, the principal vectors summation of surface and volume forces, as well as the instantaneous quantity of motion concerning the material vectors flowing through the material pipeline adjacent sections, is equal to zero. In Figure 4, the principal vector of surface forces P was directed to the right, along the *x-axis*, and the principal vector of volume forces Q was directed along the y-*axis*. The instantaneous quantities of motion $M_m \cdot \vartheta_a$ and $M_m \cdot \vartheta_b$ were directed inward, through the corresponding sections a and b. In this case, Euler's theorem used during the process was written as follows.

$$\sum X = W_{ox} + W_{nx} - M_m \vartheta_{ax} = 0;$$
$$\sum У = W_{oy} + M_m \vartheta_{by} W_{ny} - M_m \vartheta_{ay} = 0. \tag{1}$$

In the Eq. (1), M_m – instantaneous mass of material passing through the fertilizer pipe cross-section. W_{oy} = Q; W_{ox}= 0; W_{nx} = P; W_{ny} = 0. In this case, Eq. (1) took the form:

$$W_{nx} = M_n \vartheta_{ax} = P;$$
$$-W_{ny} + M_m \vartheta_{by} - M_m \vartheta_{by} = \text{Q} \tag{2}$$

At a small distance between lines a and b, the velocities of particles in lines were assumed scalarly equal ($\vartheta_{by} = \vartheta_{ay} = \vartheta$). Following the process from Eq. (2), this study obtained:

$$W_{nx} = M_m V \vartheta_{ax} = P$$
$$W_{ny} = \text{Q}. \tag{3}$$

In Eq. (3), the instantaneous mass of the material M was equal to:

$$M_m = \frac{1}{q} \gamma S \vartheta, \tag{4}$$

where: q – acceleration of free fall,
γ – specific weight of fertilizer,
S–cross-sectional area of the conduit,
ϑ – velocity of particles in the pipe,
W_o – volumetric forces,
W_n – surface forces.

Considering Eq. (4), the first equality in Eq. (3) was rewritten as:

$$W_{nx} = \frac{1}{q} \gamma S \vartheta^2 \cos(90° - \alpha). \tag{5}$$

In Eq. (5) $\frac{\gamma}{q} = \rho -$ the volumetric weight (density) of the flow material. Therefore, the last formula was rewritten as:

$$W_{nx} = \rho S N^2 \cos(90° - \alpha). \tag{6}$$

Figure 5 showed that the main vector of forces of the granules added pressure on the fertilizer pipe wall was equal to the horizontal component concerning the surface forces and was directed opposite to it.

Considering the adopted assumptions and the second equality in Eq. (3), the second equality in Eq. (2) was written in this form.

$$M_m V_{ay} - M_m V_{by} = 2\text{Q}. \tag{7}$$

In Eq. (7) $\vartheta_{ay} = \vartheta \cdot cos\alpha$, and $\vartheta_{by} = \vartheta$, taking the following form:

$$M_m \vartheta (cos\alpha - 1) = 2\text{Q}. \tag{8}$$

Eq. (8) showed that it was possible to determine the weight of the fertilizer passing through the corresponding bend of the fertilizer pipe:

$$\text{Q} = \frac{1}{2} M_m \vartheta (cos \propto -1). \tag{9}$$

In Eq. (9), it was more convenient to rewrite the instantaneous mass considering the volumetric weight:

$$M_m = \rho S \vartheta, \tag{10}$$

Then Eq. (9) took the following form:

$$Q = \frac{1}{2}\rho S \vartheta^2 (cos\alpha - 1). \tag{11}$$

During the process, the numerical values of the terms of equation Eq. (11) were obtained:
$\rho = 1.0 \frac{g}{cm^3}$ – volumetric weight of the fertilizer.
$S = \frac{\pi d^2}{4} = 7.06 cm^2$ – area of the fertilizer pipe cross-section.
$d = 3.0\ cm$ – diameter of the fertilizer pipe cross-section.
$\vartheta = 15 \frac{cm}{c}$ – the speed of the fertilizer flow through the fertilizer pipe.
$\alpha = 30°$ – the angle between the inclined and vertical parts of the fertilizer pipeline.
By substituting the numerical values in Eq. (11), the flowing mass through the fertilizer pipe cross-section was obtained:

$$Q = \frac{1}{2} 1.0 \cdot 7.06 \cdot 15^2 \cdot 0.14 = 222.39 g \frac{cm}{s^2}$$

The weight of the material used in the analysis was equal to 22.67 g. The calculation showed that a flow of material through the pipe between lines a and b (Figure 4) was stable, and it must be delivered into the fertilizer pipe at least 22.67 grams per second. At the same time, the following effort was applied to the crank part of the pipe wall: $\text{P} = W_{nx} = 1 \cdot 7006 \cdot 225 \cdot 0.5 = 794.25\ g$.

3.1.2. Fertilizer flow rate in pipes 1 and 2

The phosphate fertilizer flowed as a single stream up to the distributor and then was divided into two specified doses, which were placed at different depths, passing through the pipes 1 and 2. To obtain the required dosing rate, the following design was proposed. At the end, the pipe 5 for phosphate fertilizer supply was connected to the rectangular receiving pipe 4, into which distribution pipes 1 and 2 were mounted. As earlier mentioned, a flap 6 is mounted on the axis 7 inside of the receiving pipe 4, which was set at different angles β from the vertical axis of symmetry, ranging from 0° to π/2 and to the left or right (Figure 2, view B, pipes 1, 2). The flap axis on the outside of the tubes was rigidly connected with arrow 8, showing the angle value on dial 9 as the required angle of the flap was set. When β = 0°, the fertilizer flow rate of both pipes 1 and 2 was the same. Moreover, when β = π/2 to the left, the flow through the pipe 2 stopped. When β = π/2 to the right, the flow of fertilizer into pipe 1 stopped.

Determining the dependence of the fertilizer flow through the pipes 1 and 2 on the flap installation angle β was important. The weight of fertilizer passing through the intake receiving pipe 6 was equal to:

$$\text{Q} = eh \cdot 2b \cdot \gamma. \tag{12}$$

where, e – intake pipe length, cm,
$2b$ – intake pipe width, cm,
h – intake pipe depth, cm,
γ – volumetric weight of fertilizer in the receiving pipe, cm.

The current volume weight of the fertilizer in the intake receiving pipe was variable. However, the process was considered quasi-homogeneous in a limited volume for calculation purposes. In the influence of the flap 6, the single flow of current material was divided into two unequal flows, which were directed to the pipes 1 and 2. In this case, Eq. (12) had the following form:

$$\text{Q} = \text{Q}_1 + \text{Q}_2, \tag{13}$$

where, Q_1 – weight of fertilizer flowing into pipe 1,
Q_2 – weight of fertilizer flowing into pipe 2.

However:

$$Q_1 = V_1 \cdot \gamma;$$
$$Q_2 = V_2 \cdot \gamma \qquad (14)$$

where, V_1 and V_2 – volumes of the intake chamber of the 1st as well as 2nd pipes.

The following process showed that at $< \beta = 0$, $V_1 = V_2$, where $Q_1 = Q_2$.

Here:

$$V_1 = V_2 = beh;$$
$$Q_1 = Q_2 = beh\gamma. \qquad (15)$$

The case $0 < \beta < \pi/2$ was considered when the flap was turned to the left. Figure 3, view B, showed that the volume of the right pipe 1 increased by ΔV, and the left pipe 2 decreased via the same amount, leading to the following.

$$V_1 = beh + \Delta V = beh + \frac{1}{2}eh\Delta b;$$
$$V_2 = beh - \Delta V = beh - \frac{1}{2}eh\Delta b;$$
$$V_1 = \frac{1}{2}eh(2b + \Delta b);$$
$$V_2 = \frac{1}{2}eh(2b + \Delta b). \qquad (16)$$

The outcome showed that $2ehb = V$ in Eq. (12) was the total volume of the receiving chamber. When the above calculations were correct, then $V_1 + V_2$ in Eq. (16) equaled V. The equation was checked using the following formula, as the statements were confirmed.

$$\frac{1}{2}eh(2b + \Delta b) + \frac{1}{2}eh(2b - \Delta b) = 2ehV.$$

In Eq. (16), two variables depended on angle β, including h and Δb:

$$h = rcos\beta;$$
$$\Delta b = rsin\beta. \qquad (17)$$

Where r – flap width (radius).

Considering Eq. (17), Eq. (16) was rewritten during the process as follows:

$$V_1 = \frac{1}{2}ercos\beta \cdot (2b + rsin\beta);$$
$$V_2 = \frac{1}{2}ercos\beta \cdot (2b - rsin\beta). \qquad (18)$$

$V_1 - V_2 = \Delta V$ showed the measure of increase or decrease of fertilizer flow through the 1st as well as 2nd pipes:

$$V_1 - V_2 = \Delta V = \frac{1}{2}ercos\beta \cdot (2b + rsin\beta) - \frac{1}{2}ercos\beta \cdot (2b - rsin\beta);$$
$$\Delta V = \frac{1}{2}ercos\beta 2rsin\beta;$$
$$\Delta V = \frac{1}{2}er^2 sin\beta cos\beta. \qquad (19)$$

In the case of $\beta = 0$, the single flow Q was divided into two equal flows:

$$\beta = Q_1 = Q_2. \qquad (20)$$

When the flap was turned to the left or right, Q_1 and Q changed in a larger or smaller direction. Moreover, this change was proportional to the difference in volume ΔV, since:

$$\Delta Q = \Delta V\gamma = \frac{1}{2}er^2\gamma \cdot sin2\beta. \qquad (21)$$

From Eq. (20), there was a clear observation that:

$$Q = 2Q_1 = 2Q_2;$$
$$Q = Q_1 + Q_2. \qquad (22)$$

Considering Eq. (21):

$$Q = (Q_1 + \Delta Q) + (Q_2 - \Delta Q);$$
$$Q = (Q_1 - \Delta Q) + (Q_2 + \Delta Q). \quad (23)$$

when $\Delta Q = 0$;

$$Q = Q_1 + Q_2 = 2\frac{Q}{2}. \quad (24)$$

In this case:

$$Q_1 = \frac{1}{2} er\gamma[cos\beta \cdot (2b + rsin\beta) - r \cdot sin2\beta]$$
$$Q_2 = \frac{1}{2} er\gamma[cos\beta \cdot (2b + rsin\beta) + r \cdot sin2\beta] \quad (25)$$

In Eq. (23) Q_1 and Q_2 were set values, which depended on the additional flow ΔQ, and also directly relied on the flap setting angle β. To establish these dependences, the formula had the numerical values of design and technological parameters as already set factors:

e = 30 mm – pipe length,

$r = b = 30\ mm$ – pipe width, flap radius,

$\gamma = 1{,}0\frac{g}{cm^3}$ – volume weight of granulated mineral fertilizer.

Figure 5 showed the numerical values and graphical representation concerning the dependence of the surplus flow of mineral fertilizer, with minus for the branch pipe, where the flap was turned in. The dependence also had the branch pipe where the flap was turned away on the angle of its installation, counted from the vertical axis. Dependences were calculated for different pipe length e = 2.5; 3.0; 3.5; 4.0 (Figure 2, view A–A), according to Eq. (21). Figure 5 showed that with the increase of the flap angle β the value of flow in branch pipe 2 (where the flap was turned) decreased, as the addition flow with minus increased. At the same time, the flow in pipe 1 increased by the same amount. This process continued until complete cessation of the flow in branch pipe 2, when $\beta = \pi/2$ – branch pipe was completely closed. However, the curve $\Delta Q = f(\beta)$ rose to β = 45° then monotonically descended to the abscissa, to zero. This phenomenon was explained that the outflow Q also depended on h – the depth of the intake pipe, Eq. (12), relying on the installation angle β, Eq. (17). Using the graphs in Figure 5, it was possible to mark dial 9 (Figure 2, view B), for the distribution of mineral fertilizer through the pipes 1 and 2 (such as ¼, ½, etc.), depending on the required application rate.

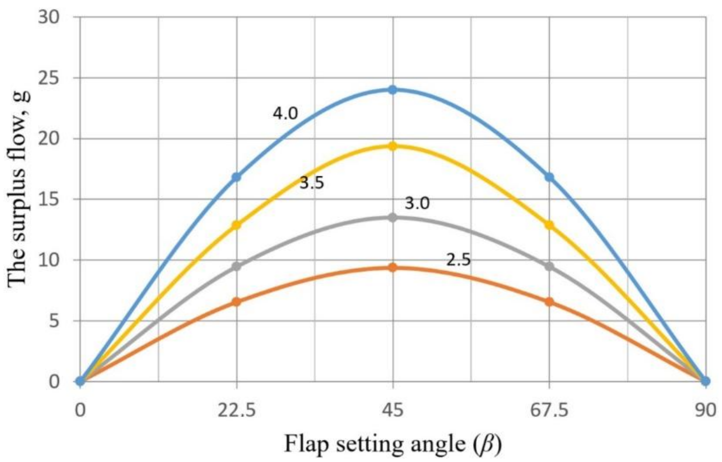

Figure 5 Dependence of fertilizer surplus flow rate on the flap setting angle

In the earlier discussion, the capacity of individual pipes was not considered. When necessary, the obtained dependences were multiplied by the velocity of material flow through the pipes, and the per-second output was obtained. In this part of the study, the material was divided into two flows in relation. For example:

$$Q_1 = 0{,}5Q; \qquad Q_1 = 0{,}75Q;$$
$$Q_2 = 0{,}5Q; \qquad Q_2 = 0{,}25Q;$$
$$Q_1 + Q_2 = Q; \qquad 0{,}75Q_1 + 0{,}25Q_2 = Q,$$

where Q was the total sowing (output) of pipes 1 and 2.

Although these ratios were estimated in the form of surplus or surplus flow from the nominally set working body value on each of the two pipes, as Figure 6 showed the flow. For comparison with the experimental result, the value of the nominal flow was added to the surplus flow.

3.2. The flow rate dependence of mineral fertilizer granules through the pipe on pipe installation height and angle

The phosphate mineral fertilizer that was divided into two streams flowed by gravity down the inclined pipes and then spread to the subsoil bed. The particle velocities through the pipes were determined to ensure that the fertilizer was delivered following the specified application rate.

During the process, the behavior of a mineral fertilizer granule (M) resting inside the pipe was considered. The granule rested under the action of the following forces, as shown in Figure 6.

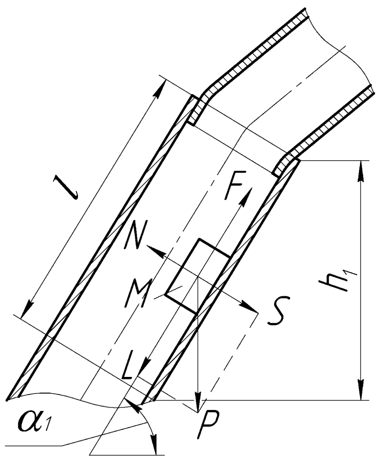

Figure 6 Granule movement in the pipe

P – weight of the granule M,
N– normal pressure of the pipe inner surface on the granule,
F– friction force between the granule and the pipe surface,
S– force equivalent to the normal pressure,
L – granule moving force,

The granule was in an equilibrium state when:

$$L = F, L = Psin\alpha_1; F = fN; \tag{26}$$

where, $N = S = Pcos\alpha_1$ and $P = mg$.

Substituting the values of the quantities included in Eq. (26) as the process obtained:

$$mgsin\alpha_1 = fmqcos\alpha_1,$$

where f – friction coefficient between granule and pipe surface,

g – acceleration of free fall.

From the last expression, the process led to the following:

$$tg\alpha_1 = tg\varphi;$$
$$\alpha_1 \geq \varphi \tag{27}$$

where φ – friction angle between the granule and the material. Inequality Eq. (27) showed that a stable flow of fertilizer granules through the inclined pipe, the pipe inclination angle to the soil surface was greater than the fertilizer friction angle against the metal.

From classical mechanics, it was known that the force moving the granule was equal to:

$$L = ma. \tag{28}$$

where a is the acceleration of the granule motion expressed through the initial and final velocities of the granule was expressed as follows:

$$a = \frac{\vartheta_k - \vartheta_0}{\Delta t}, \tag{29}$$

where ϑ_0 – initial velocity of the granule,
ϑ_k – final velocity of the granule,
Δt – travel time of the granule through the fertilizer pipe.
Here:

$$\Delta t = \frac{l}{\vartheta_{av}}, \tag{30}$$

where, l – fertilizer pipe length,
ϑ_{av} – average velocity of granules along the fertilizer pipe, and it was equal to:

$$\vartheta_{av} = \frac{\vartheta_k + \vartheta_0}{2}. \tag{31}$$

In a steady-state process, the initial velocity of the granules was equated to the linear velocity of the sowing spool surface which was expressed as follows:

$$\vartheta_0 = \omega r_1 = \frac{\pi n}{30} r_1, \tag{32}$$

where, n – metering unit (spool) rotation speed,
ω – spool angular velocity,
r_1 – spool radius.
From Eq. (31) and (30), the following equation was obtained:

$$\Delta t = \frac{2l}{\vartheta_k + \vartheta_0}. \tag{33}$$

In Eq. (33) and (29), the following equation was achieved:

$$a = \frac{\vartheta_k - \vartheta_0}{2l} \cdot (\vartheta_k + \vartheta_0);$$

$$a = \frac{sin\alpha_1}{2h_1} \cdot \left(\vartheta_k^2 - \vartheta_0^2\right). \tag{34}$$

From Eq. (28), 26), and (34), the following equation was obtained:

$$mqsin\alpha_1 = \frac{m \cdot sin\alpha_1}{2h_1}\left(\vartheta_k^2 - \vartheta_0^2\right);$$

$$\vartheta_k^2 = \vartheta_0^2 + 2qh_1;$$

$$\vartheta_k = \sqrt{\vartheta_0^2 + 2qh_1}, \tag{35}$$

where, h_1 – granule drop height.

During the process, formulas Eq. (32) and (34) allowed determining the average velocity of the granule according to Eq. (31) that it possible to establish the mineral fertilizer dosing rate. To assess the adequacy of the obtained results, the set problem was important by considering the work of the friction force.

In Eq. (26), the value of N was expressed as follows:

$$N = mqcos\alpha_1 = mq\sqrt{1 - sin^2\alpha_1}. \tag{36}$$

However,

$$sin\alpha_1 = \frac{h_1}{l}.$$

At that:

$$N = \frac{mq}{l}\sqrt{l^2 - h_1^2}, \tag{37}$$

In this case, the friction force was equal to:

$$F = \frac{1}{l} fmq\sqrt{l^2 - h_1^2}. \tag{38}$$

The friction force work along the path of the movement of the granule down the fertilizer pipe was determined according to the formula, $R = Fl$.

Considering Eq. (38), the equation was:

$$R = fmq\sqrt{l^2 - h_1^2}. \tag{39}$$

Laws of mechanics showed that at the end path of the granule down the sloping pipe, the work of the friction force, as well as kinetic energy, added up and equated to potential energy:

$$Э_n = Э_k + R, \tag{40}$$

where,

$$Э_k = \frac{m\vartheta^2}{2}.$$

When the values of the quantities included in Eq. (40) were substituted, the equation was as follows:

$$mqh_1 = \frac{m\vartheta^2}{2} + fmq\sqrt{l^2 - h_1^2}.$$

Reducing all components by m and transforming, the following equation was obtained:

$$\vartheta = \sqrt{2qh_1\left(1 - \frac{f}{tq\alpha_1}\right)}. \tag{41}$$

Eq. (41) allowed determining the velocity of the granule at the path end l along the fertilizer pipe. In addition, the ϑ_{av} was determined, which allowed setting the fertilizer application dosage. For numerical representation of the obtained dependences, the values included in Eq. (35) and (41) were obtained:

q = 981.0 cm/s^2 – acceleration of free fall,
h_1 = 50 cm – granule transport height,
f = 0.6 – coefficient of friction between granules and metal,
n = 30 rpm – number of revolutions of the metering unit per minute,
r_1 = 2.0 cm – radius of the metering spool,
α_1 = 60° – fertilizer pipe installation angle.

According to Eq. (35) and (41), this study obtained the following:

1. $\vartheta_k = \sqrt{\vartheta_0^2 + 2qh_1} = \sqrt{\left(\frac{3.14 \cdot 30}{30}\right)^2 + 2 \cdot 981 \cdot 50} = 3.13\ m/s.$
2. $\vartheta = \sqrt{2qh_1\left(1 - \frac{f}{tga_1}\right)} = \sqrt{2 \cdot 981 \cdot 50 - \frac{0.6}{1.73}} = 2.52\ m/s.$

The result according to Eq. (35) exceeded the outcome according to Eq. (41) by 24%. This was explained that in the first variant, the friction on the fertilizer pipe was not considered, and the assumption was acceptable in simplified calculations. As a result, the second variant was more acceptable for practical application. The final choice was made after comparing the outcomes with the results of the experimental study.

When Eq. (41) was analyzed, the velocity of the granule in the pipe was influenced by three variable factors, namely the height of the pipe h_1, the friction coefficient between granule and metal f, as well as the angle of installation α_1. Following the discussion, the friction coefficient was independent of the design parameters. Therefore, the influence of the pipe installation angle and its (pipe) height on the granule flow rate was investigated.

Figure 7 showed the dependence of mineral fertilizer granules flow rate through the pipe on the pipe installation angle (α_1) and the drop height (h_1). The outcome showed that as the installation angle increased, the flow velocity improved. Therefore, at the granule drop height h_1 = 50 cm, doubling the installation angle α_1 from 30° to 60° led to an increase in the velocity, from 1.29 m/s to 2.54 m/s. This trend was maintained in all considered drop heights during the process. Increasing the drop height twice from h_1 = 30 cm to h_1 = 60 cm, at a constant angle of installation α_1 = 60°, multiplied the outlet velocity by 41%, from 1.97 to 2.78 m/s.

Figure 7 showed the graphical dependence of the granule flow velocity on the drop height (dashed line). The variables were used to define the values of the optimal variables, providing the given velocity of granule flow. Consequently, the intersection of the curves, h_1 = 50 cm and α_1 = 47° was pointed to at α_1 = 47° and h_1 = 53 cm. At the specified mode of operation of the fertilizer pipe, the granule flow velocity of 2.72 m/s was provided. These values were allowed to determine the hopper installation height during the process.

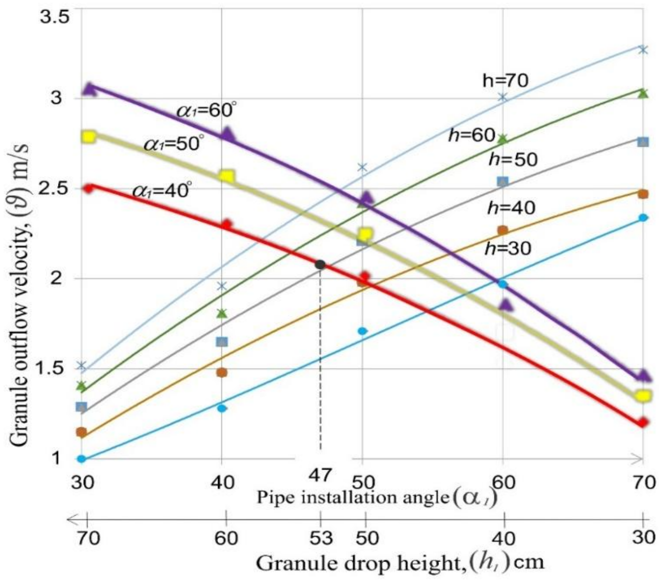

Figure 7 Dependence of the granule flow rate on the drop height and pipe installation angle

3.3. Results of experimental studies

3.3.1. Flap-setting angle

Figure 8 showed that by varying the flap position, the dependence of the changes in the seed quantity for each distribution pipes on the flap-setting angle was obtained. Laboratory experiments signified that uniform distribution through pipes 1 and 2 (the outlets for placing depths of 16–18 and 22–25 cm) was obtained at the flap installation angle β = 25°–27°. In this position of the flap, almost the same amount of sowing of fertilizer granules from each pipe was obtained. Moreover, the graph showed that when the amount of fertilizer in one pipe decreased, the amount in the other pipe increased equally.

The adequacy of the theoretical dependence (21) by the experimental data was shown in the following analysis. At the flap installation angle of 22.5˚, the incremental flow was equal to 16.8 units. Additionally, at the installation angle of 45˚, the incremental flow was equal to 24 units. The excess was also equal to 42.8% as shown in Figure 5. The excess outflow at the same angles during the experimental studies varied from 100 to 143 grams, with 43%, and the coincidence was adequate and applicable.

Depending on the soil condition, different fertilizer doses were set at all three fertilizer application levels irrespective of the total cultivation depth. This was a distinctiveness of the proposed technology and technical solutions.

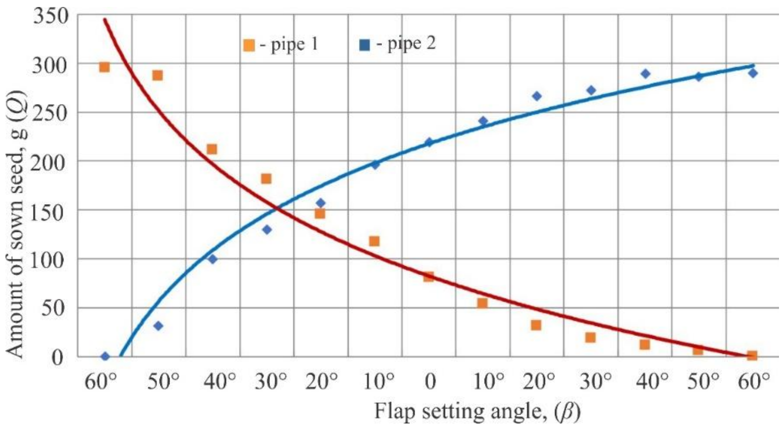

Figure 8 Dependence of the seed quantity on the flap-setting angle

3.3.2. Field experiments

Field experiments were conducted according to technical assignment and agrotechnical requirements for the Northern as well as Central Kazakhstan conditions, as the results of experiments were shown in Table 1. Experiments showed that the unevenness of fertilizer distribution from the pipes 1 and 2 of the distributor varied between 9–13 %. Moreover, the field surface after the deep loosener-fertilizer pass was characterized by a slight increase in ridging on the trail of working bodies.

Table 1 Quality indicators of the tiered application technological process of mineral fertilizer

Name of indicators	Indicator values according to technical assignment; agrotechnical requirements*	Indicator values according to test data
Operating mode:		
- machine speed, m/s	2.44	2.44
- set working depth, cm	22–25 (20–22)	27
Field surface ridging, cm	no more than 5	4–6
Fertiliser dosage, kg/ha:		
Maximum	400* (100–400)	400
Minimum	50*	50
Seeding unevenness between machines, %	15*	11,3
Uneven distribution between pipes 1 and 2, %	no more than 50	9...13
Depth of embedding, cm	6–25	6–27
- first layer	8–10	6–10
- second layer	16–18	15,5–18,6
- third layer	23–25	22–27

Comparative analyses of the peculiarity of the proposed working body with existing machines showed that there are many similar implements and are often used to apply fertilizer at one level (Nukeshev et al., 2023b; Salar et al., 2021; Patuk et al., 2020; Qi et al., 2020; Mandal and Thakur, 2010). The results of the review study indicated that the existing commercial equipment for in-soil application of fertilizer, such as Agro-Masz, Volmer, Pottinger, Bednar, Agrisem, and Claidon, could apply fertilizer only on first or second layers, depending on the depth of cultivation. Many versions of the subsoiler were implemented with a straight chisel (Salar et al., 2021; Patuk et al., 2020; Qi et al., 2020; Akbarnia et al., 2018), but the bent chisel version used in this study contributed to excellent soil loosening.

Previous studies used the three-tier intra-soil differentiated fertilizer application method. However, the working body was designed for one type of fertilizer, as the depth of application was not variable (Nukeshev, 2023b; 2022; 2021).

The proposed method was suitable for both autumn and deep fallow tillage with simultaneous differentiated application of basic doses of one/two types of mineral fertilizer (up to 400 kg/ha) obliquely in three tiers in the soil. At the same time, the model allowed changing the placement depths independently of the tillage depth, decompacting the soil up to 40 cm. Additionally, the placement depth and distance between the layers were adjustable, which made it possible to plan the fertilizer application depending on the type of plant and root system.

4. Conclusions

In conclusion, the technological scheme of tiered application of two types of mineral fertilizer was justified concerning plant needs and physiology of the root system development, as well as the plant growth. The given theoretical calculations allowed this study to justify the design and technological parameters of the proposed device depending on the established application rate of mineral fertilizer. During the analysis, laboratory experiments show that uniform distribution through pipes 1 and 2, having the outlets for placing depths of 16–18 cm as well as 22–25 cm, can be obtained at the flap installation angle of β = 25°–27°. The obtained nomogram of changing the sowing quantity through the distributor pipes according to the flap-setting angle shows that when the amount of fertilizer in one pipe decreases, the amount in the other pipe increases symmetrically. Assuming the condition of ensuring the required fertilizer granule flow velocity, the pipe installation angle (α_1 = 47°) and pellet drop height (h_1 = 53 cm) have been determined that define the installation height of the elastic pipes (and hopper) of the developed deep loosener-fertilizer. Moreover, field tests show that the unevenness of fertilizer distribution from pipes 1 and 2 of the distributor varies between 9–13 %. The developed fertilizer unit provides regulation of fertilizer application depths of 8-10 cm, 16-18 in pairs, and 23-25 cm depths separately, irrespective of the total depth of cultivation up to 40 cm. This allows farmers to use the product in any soil-climatic zones with different humus horizons for application of differentiated fertilizer doses at all three levels.

Acknowledgements

This study is funded by the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan (Grant No. AP19674514).

Author Contributions

Sayakhat Nukeshev: Supervision, Conceptualization, Writing - review & editing, Funding acquisition, Project administration. **Dzhadyger Eskhozhin:** Writing - original draft Resources, Methodology. **Yerzhan Akhmetov:** Investigation, Data curation, Formal analysis. **Khozhakeldi Tanbayev:** Writing - review & editing, Investigation, Resources, Visualization. **Adilet Sugirbay:** Resources, Visualization **Shezhau Kadylet:** Resources.

Conflict of Interest

The authors declare that there are no known competing financial interests or personal relationships that could have appeared to influence the work reported in this study.

References

Abella, GPL, Lansigan, F & Tubay, J 2021, 'Agricultural Land Use Allocation under Current and Projected Scenarios', *International Journal of Technology*, vol. 12, no. 5, pp. 975–988, https://doi.org/10.14716/ijtech.v12i5.5179

Ahmad, W, Farmanullah, N, Shah, Z, Jamal, M & Shah, KA 2013, 'Recovery of organic fertility in degraded soil through fertilization and crop rotation', *Journal of the Saudi Society of Agricultural Sciences*, vol. 13, no. 2, pp. 92–99, https://doi.org/10.1016/j.jssas.2013.01.007

Akbarnia, A, Asghar Mohammadi, M & Alimardani, R 2014, 'Simulation of draft force of winged share tillage tool using artificial neural network model', *Agricultural Engineering International: CIGR Journal*, vol. 16, no. 4, pp. 57–65, https://cigrjournal.org/index.php/Ejounral/article/view/3022/1967

Azevedo, RP, Salcedo, IH, Lima, PA, Fraga, VDS & Lana RMQ 2018, 'Mobility of phosphorus from organic and inorganic source materials in a sandy soil', *International Journal of Recycling of Organic Waste in Agriculture*, vol. 7, pp. 153–163, https://doi.org/10.1007/s40093-018-0201-2

Bai, J, Zhang, S, Huang, S, Xu, X, Zhao, S, Qiu, S, He, P & Zhou, W 2023, 'Effects of the combined application of organic and chemical nitrogen fertilizer on soil aggregate carbon and nitrogen: A 30-year study', *Journal of Integrative Agriculture*, vol. 22, no. 11, pp. 3517–3534, https://doi.org/10.1016/j.jia.2023.09.012

Fagodiya, RK, Sharma, G, Verma, K, Rai, AK, Prajapat, K, Singh, R, Chandra, P, Sheoran, P, Yadav, RK & Biswas, A 2024, 'Computation of soil quality index after fifteen years of long-term tillage and residue management experiment (LT&RE) under rice wheat system', *Agricultural Systems*, vol. 219, article 104039, https://doi.org/10.1016/j.agsy.2024.104039

Gunawan, G, Sutjiningsih, D & Soeryantono, HW 2013, 'Soil erosion estimation based on GIS and remote sensing for supporting integrated water resources conservation management', *International Journal of Technology*, vol. 4, no. 2, pp. 147–156, https://doi.org/10.14716/ijtech.v4i2.110

Hobson, D, Harty, M, Tracy, SR & McDonnell, K 2022, 'The effect of tillage depth and traffic management on soil properties and root development during two growth stages of winter wheat (Triticum aestivum L.)', *Soil*, vol. 8, pp. 391–408, https://doi.org/10.5194/soil-8-391-2022

Houshyar, E & Esmailpour, M 2018, 'The impacts of tillage, fertilizer and residue managements on the soil properties and wheat production in a semi-arid region of Iran', *Journal of the Saudi Society of Agricultural Sciences*, vol. 19, no. 3, pp. 225–232, https://doi.org/10.1016/j.jssas.2018.10.001

Jie, C, Jing-Zhang, C, Man-Zhi, T & Zi-Tong, G 2002, 'Soil degradation: a global problem endangering sustainable development', *Journal of Geographical Sciences*, vol. 12, pp. 243–252, https://doi.org/10.1007/BF02837480

Johnston, J, Fixen, P & Poulton, P 2015, 'Efficient use of phosphorus fertilisers in farming', *Plant Nutrition*, vol. 2, pp. 8–11, http://eeca-ru.ipni.net/article/EECARU-2287

Khole, P, Saumya, S & Jain, KK 2016, 'Effect of winged subsoiler on soil characteristics and subsoiler draft', *Advances in Life Sciences Conference*, vol. 5, no. 18, pp. 784–7849, https://www.researchgate.net/publication/331708778

Li, W, Gu, X, Du, Y, Zheng, X, Lu, S, Cheng, Z, Cai, W & Chang, T 2023, 'Optimizing nitrogen, phosphorus, and potassium fertilization regimes to improve maize productivity under double ridge-furrow planting with full film mulching', *Agricultural Water Management*, vol. 287, article 108439, https://doi.org/10.1016/j.agwat.2023.108439

Lishchuk, A, Parfenyk, A, Horodyska, I, Boroday, V, Ternovyi, Y & Tymoshenko, L 2023, 'Environmental risks of the pesticide use in agrocenoses and their management', *Journal of Ecological Engineering*, vol. 24, no. 3, pp. 199–212, https://doi.org/10.12911/22998993/158537

Liu, X, Zhang, X, Wang, YX, Sui, Y, Zhang, S, Herbert, S & Ding, G 2018, 'Soil degradation: a problem threatening the sustainable development of agriculture in Northeast China', *Plant Soil and Environment*, vol. 56, pp. 87–97, https://doi.org/10.17221/155/2009-PSE

Mandal, S & Thakur, TC 2010, 'Design and development of subsoiler-cum-differential rate fertilizer applicator', *Agricultural Engineering International: the CIGR Ejournal*, vol. 12, no. 1394, pp. 74–83

Mazhitova, Z, Shamshidenova, F, Isakhan, G, Kurmangali, G, Azmukhanova, A, Zhalmurzina, A & Bibizhamal, O 2023, 'Environmental consequences of virgin and fallow lands development in Kazakhstan', in Beskopylny, A, Shamtsyan, M & Artiukh, V (eds), *INTERAGROMASH 2022*, Lecture Notes in Networks and Systems, pp. 2327–2337, https://doi.org/10.1007/978-3-031-21219-2_261

Meyer, G, Bell, MJ, Kopittke, PM, Lombi, E, Doolette, CL, Brunetti, G, Klysubun, W & Janke, CK 2022, 'Mobility and lability of phosphorus from highly concentrated fertiliser bands', *Geoderma*, vol. 429, pp. 116248, https://doi.org/10.1016/j.geoderma.2022.116248

Mujiyo, N, Nariyanti, S, Suntoro, N, Herawati, A, Herdiansyah, G, Irianto, H, Riptanti, EW & Qonita, A 2022, 'Soil fertility index based on altitude: A comprehensive assessment for the cassava development area in Indonesia', *Annals of Agricultural Sciences*, vol. 67, no. 2, pp. 158–165, https://doi.org/10.1016/j.aoas.2022.10.001

Nukeshev, S, Eskhozhin, D, Lichman, G, Karaivanov, D, Zolotukhin, E & Syzdykov, D 2016, 'Theoretical substantiation of the design of a seeding device for differentiated intra soil application of mineral fertilizer', *Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis*, vol. 64, no. 1, pp. 115–122, https://acta.mendelu.cz/pdfs/acu/2016/01/12.pdf

Nukeshev, S, Yeskhozhin, K, Akhmetov, Y, Kossatbekova, D, Tleumbetov, K & Tanbayev, K 2023a, 'Traction force investigation of the new working body of the sod seeder', *International Journal of Technology*, vol. 14, no. 3, pp. 536–548, https://doi.org/10.14716/ijtech.v14i3.6008

Nukeshev, S, Yeskhozhin, K, Karaivanov, D, Ramaniuk, M, Akhmetov, E, Saktaganov, B & Tanbayev, K 2023b, 'A chisel fertilizer for in-soil tree-layer differential application in precision farming', *International Journal of Technology*, vol. 14, no. 1, pp. 109–118, https://doi.org/10.14716/ijtech.v14i1.5143

Nukeshev, SO 2021, 'Loosener-fertilizer (Kazakhstan /Astana Patent No. KZ B 34847)', *RGP 'National Institute of Intellectual Property' of The Ministry of Justice of The Republic of Kazakhstan*, no. 3, 22.01.2021, https://gosreestr.kazpatent.kz/Invention/Details?docNumber=318296

Nukeshev, SO 2022, 'Loosener-fertilizer (Kazakhstan /Astana Patent No. KZ B 35686)', *RGP 'National Institute of Intellectual Property' of The Ministry of Justice of The Republic of Kazakhstan*, no. 21, 27.05.2022, https://gosreestr.kazpatent.kz/Invention/Details?docNumber=339167

Patuk, I, Hasegawa, H, Borodin, I, Whitaker, A & Borowski, P 2020, 'Simulation for design and material selection of a deep placement fertilizer applicator for soybean cultivation', *Open Engineering*, vol. 10, no. 1, pp. 733–743, https://doi.org/10.1515/eng-2020-0082

Qi, JT, Tian, XL, Li, Y, Fan, XH, Yuan, HF, Zhao, JL & Jia, H 2020, 'Design and experiment of a subsoiling variable rate fertilization machine', *International Journal of Agricultural and Biological Engineering*, vol. 13, no. 4, pp. 118–124, https://www.ijabe.org/index.php/ijabe/article/view/5757

Qin, Y, Li, X, Wu, Y, Wang, H, Han, G & Yan, Z 2023, 'The effect of soil enzymes and polysaccharides secreted by the roots of Salvia miltiorrhiza Bunge under drought, high temperature, and nitrogen and phosphorus deficits', *Phyton-International Journal of Experimental Botany*, vol. 93, no. 1, pp. 119–135, https://doi.org/10.32604/phyton.2023.046075

Rust, N, Lunder, OE, Iversen, S, Vella, S, Oughton, EA, Breland, TA, Glass, JH, Maynard, CM, McMorran, R & Reed, MS 2022, 'Perceived causes and solutions to soil degradation in the UK and Norway', *Land*, vol. 11, no. 1, article 131, https://doi.org/10.3390/land11010131

Ryan, B & Bristow, DN 2023, 'Climate change and hygrothermal performance of building envelopes: A review on risk assessment', *International Journal of Technology*, vol. 14, no. 7, pp. 1461–1475, https://doi.org/10.14716/ijtech.v14i7.6666

Salar, MR, Karparvarfard, SH, Askari, M & Kargarpour, H 2021, 'Forces and loosening characteristics of a new winged chisel plough', *Research in Agricultural Engineering*, vol. 67, pp. 17–25, https://doi.org/10.17221/71/2020-RAE

Saparov, A 2013, 'Soil resources of the Republic of Kazakhstan: Current status, problems and solutions', *Environmental Science and Engineering*, pp. 61–73, https://doi.org/10.1007/978-3-319-01017-5_2

Saprykina, N 2023, 'Ecological approaches to the sustainable development of agrocenoses in the context of food security', *E3S Web of Conferences*, vol. 431, article 01008, https://doi.org/10.1051/e3sconf/202343101008

Sheujen, AH 2016, 'Agrochemistry Part 3. Experimental agrochemistry', *Krasnodar*, vol. 3, pp. 572–587, https://kubsau.ru/upload/iblock/0d3/0d3ad8b60d5e1eea0c7f87c8242060f2.pdf

Shmulevich, I, Asaf, Z & Rubinstein, D 2007, 'Interaction between soil and a wide cutting blade using the discrete element method', *Soil and Tillage Research*, vol. 97, no. 1, pp. 37–50, https://doi.org/10.1016/j.still.2007.08.009

Song, W, Jiang, X, Li, L, Ren, L & Tong, J 2022, 'Increasing the width of disturbance of plough pan with bionic inspired subsoilers', *Soil and Tillage Research*, vol. 220, article 105356, https://doi.org/10.1016/j.still.2022.105356

Sugirbay, A, Zhao, K, Liu, G, Hu, G, Chen, J, Mustafin, Z, Iskakov, R, Kakabayev, N, Muratkhan, M, Khan, V, Chen Y & Zhang, S 2023, 'Double disc colter for a zero-till seeder simultaneously applying granular fertilizer and wheat seeds', *Agriculture*, vol. 13, article 1102, https://doi.org/10.3390/agriculture13051102

Tanbayev, K, Nukeshev, S & Sugirbay, A 2022, 'Performance evaluation of tillage knife discharge microchannel', *Acta Technologica Agriculturae*, vol. 25, no. 4, pp. 169–175, https://doi.org/10.2478/ata-2022-0025

Tanbayev, K, Nukeshev, S, Engin, T & Saktaganov, B 2023, 'Flat spray nozzle for intra-soil application of liquid mineral fertilizer', *Acta Technologica Agriculturae*, vol. 26, no. 2, pp. 65–71, https://doi.org/10.2478/ata-2023-0009

Tang, S, Pan, W, Zhou, J, Ma, Q, Yang, X, Wanek, W, Marsden, KA, Kuzyakov, Y, Chadwick, DR, Wu, L, Gregory, AS & Jones, DL 2024, 'Soil nitrogen and phosphorus regulate decomposition of organic nitrogen compounds in the Rothamsted Experiment', *Soil Biology and Biochemistry*, vol. 196, pp. 109502, https://doi.org/10.1016/j.soilbio.2024.109502

Wang, X, Zhou, H, Huang, Y & Ji, J 2022, 'Variation of subsoiling effect at wing mounting heights on soil properties and crop growth in wheat–maize cropping system', *Agriculture*, vol. 12, no. 10, pp. 1684, https://doi.org/10.3390/agriculture12101684

Wardak, DLR, Padia, FN, De Heer, MI, Sturrock, CJ & Mooney, SJ 2024, 'Zero-tillage induces significant changes to the soil pore network and hydraulic function after 7 years', *Geoderma*, vol. 447, pp. 116934, https://doi.org/10.1016/j.geoderma.2024.116934

Wei, P, Shi, F, Wang, X, Peng, S, Chai, R, Zhang, L, Zhang, C, Luo, L & Siddique, KH 2024, 'Optimizing rice yield and phosphorus use efficiency through root morphology and soil phosphorus management in agricultural soils', *Annals of Agricultural Sciences*, vol. 69, no. 1, pp. 53–66, https://doi.org/10.1016/j.aoas.2024.06.003

Wu, G, Wei, L, Shang, W, Wang, J, Yuan, M, Chen, Q, Sun, Y & Zhang, S 2024, 'Seasonal alternation of soil phosphorus saturation in rice-wheat rotation systems under multiple fertilization strategies', *Journal of Agriculture and Food Research*, vol. 18, article 101468, https://doi.org/10.1016/j.jafr.2024.101468

Zavalin, AA, Sokolov, OA & Shmyreva, NYa 2018, 'Nitrogen in agrosystem on chernozem soils', *RAS*, article 180, https://new.ras.ru/work/publishing/monographs/azot-v-agrosisteme-na-chernozemnykh-pochvakh

Zilio, M, Pigoli, A, Rizzi, B, Goglio, A, Tambone, F, Giordano, A, Maretto, L, Squartini, A, Stevanato, P, Meers, E, Schoumans, O & Adani, F 2023, 'Nitrogen dynamics in soils fertilized with digestate and mineral fertilizer: A full field approach', *The Science of the Total Environment*, vol. 868, article 161500, https://doi.org/10.1016/j.scitotenv.2023.161500