

Research Article

Calculation of the Working Body of a Potato Planting Machine for Applying Mineral Fertilizers Under the Soil

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Abstract

The article presents an in-depth analysis of various structural solutions for the working bodies of potato planting machines designed to apply mineral fertilizers simultaneously with planting operations. Based on the conducted research, an innovative design of a furrow opener was developed, which is equipped with a specialized spreader intended for subsurface placement of mineral fertilizers during the potato planting process. The distinctive feature of this spreader is its configuration—a freely rotating ring outfitted with oppositely oriented blades, which ensures uniform dispersion. Through theoretical modeling and calculations, the optimal geometric and operational parameters of this working unit were determined. The study substantiates that the implementation of the proposed design significantly enhances the uniformity of fertilizer distribution both in terms of lateral spread and depth within the potato ridge, thereby improving agronomic efficiency and contributing to better crop development.

Keywords

Potato Planter, Furrow Opener, Spreader, Hiller, Frame, Fertilizer Tube, Fertilizer, Soil, Potato Ridge

1. Introduction

In recent years, great attention has been paid to the sub-surface application of mineral fertilizers during potato planting as a key factor in increasing potato yield. Any technologies used for fertilizer application must ensure the required nutrient area for the plants. Numerous studies have shown that rational crop rotation contributes to a 10-15% yield increase, fertilizer systems — 40-50%, high-quality soil cultivation and crop maintenance — 20-30%, and the introduction of new

potato varieties and the use of high-quality seed material — 15-20% [1-5]. Thus, progressive technologies that intensify the effect of the second and third factors represent a significant reserve for increasing the yield of agricultural crops, including potatoes [6-11]. Currently, in order to better meet the plant's need for mineral fertilizers during the growth phase, a system of layered fertilizer placement in the soil is used, consisting of three stages: basic application, pre-sowing

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Received: 27 June 2025; **Accepted:** 9 July 2025; **Published:** 30 July 2025



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application, and plant top dressing [8, 9]. In this case, fertilizers are incorporated deeply, and under such conditions, young plants with weakly developed root systems almost do not use the fertilizers [3]. The issues of fertilizer application methods and the development of working tools and units based on them to ensure high-quality application, incorporation, and distribution of fertilizers in the soil have been considered in the works of N. Komilov [5], N. V. Lipatov [12], A. E. Zimmermann [13], and others. N. V. Lipatov proposed a ridge-forming cultivator-fertilizer applicator, which includes a supporting frame with a hitch, support wheels, fertilizer metering devices, and ridge formers (Figure 1). In this cultivator, the fertilizer application rate is regulated by shutter gates. However, during the operation of this machine, it was revealed that the fertilizer is applied in a single line along the ridge, which worsens the distribution of nutrients in the volume of the potato bed.

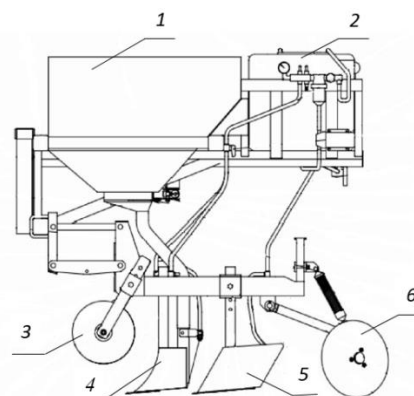


Figure 1. Ridge-forming cultivator-fertilizer applicator.

1 - solid mineral fertilizer hopper; 2 - liquid mineral fertilizer tank; 3 - support wheel; 4 - fertilizing furrow opener; 5 - hilling share; 6 - ridge-forming coverer.

A. E. Zimmerman developed a new working unit of the seeder-cultivator for subsurface broadcast sowing to eliminate these shortcomings (Figure 2).

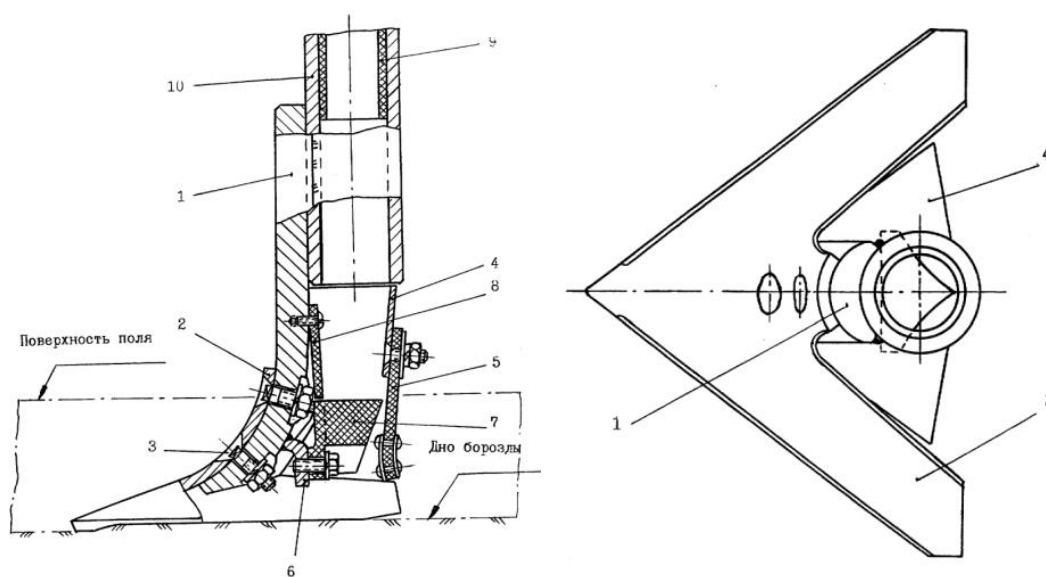


Figure 2. Working unit of the seeder-cultivator for subsurface broadcast sowing.

a) side view b) top view 1 - share; 2 - blade; 3 - bolt; 4 - tray; 5 - seed deflector; 6 - deflector; 7 - spreader; 8 - guide; 9 - seed tube; 10 - tubular stand

The disadvantage of this device is that the distribution of mineral fertilizers occurs in a horizontal layer, which hinders the absorption of nutrients by the plant root system. Analysis of the conducted studies shows that these working units and aggregates do not meet the fundamental principle of agrochemistry: “feed the plant, not the soil” [1]. To increase the availability of fertilizers to the plant root system, working units are needed that enable the application of fertilizers directly within the root zone.

2. Materials and Research Results

To eliminate these shortcomings, a new design of a universal potato planter (Figure 3) with a newly developed furrow opener for subsurface fertilizer application across the width of the potato ridge was developed in collaboration with scientists from the Ryazan State Agrotechnological University [12, 14].

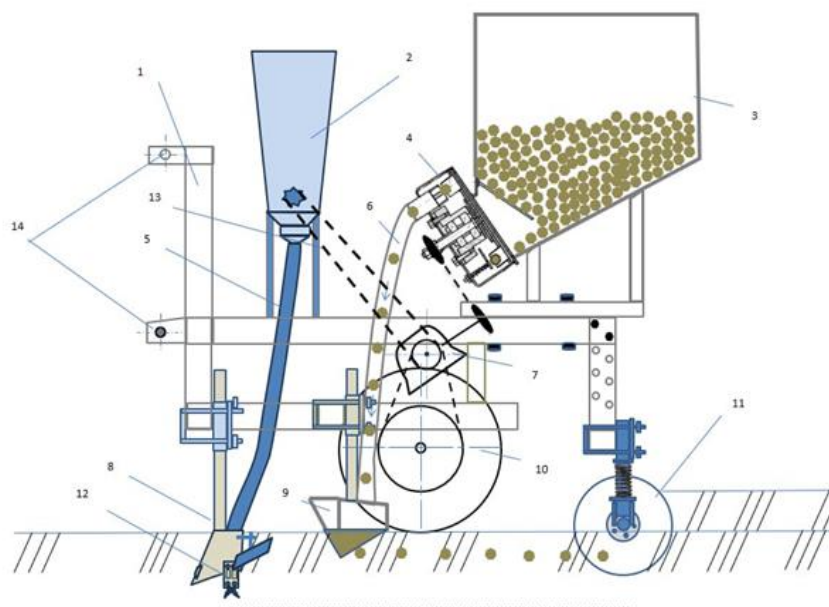


Figure 3. Structural and technological diagram of the machine for single-pass fertilizer application during potato planting.

1 - frame; 2 - fertilizer hopper; 3 - potato seed hopper; 4 - disc metering device; 5 - fertilizer tube; 6 - seed tube; 7 - gearbox; 8 - improved furrow opener for fertilizers; 9 - furrow opener for potato seed placement; 10 - support-drive wheels; 11 - furrow-forming disc; 12 - slat fertilizer spreader; 13 - chain drive; 14 - suspension.

The furrow opener we developed (Figure 4) consists of components mounted on a vertical tubular stand 1, including a loosener 2, hillers 3 and 4, fertilizer tube 5, furrow coverers 7 and 8, and a spreader 11. The spreader is made in the form of a freely rotating ring 9 with oppositely directed slats 10.

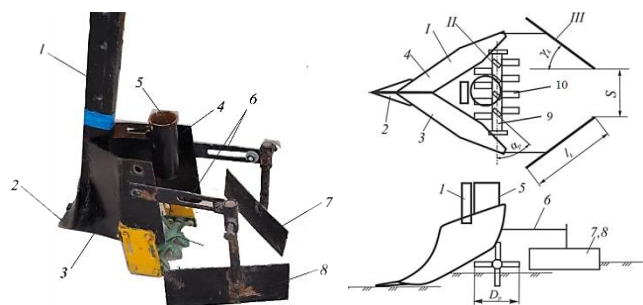


Figure 4. Working unit for simultaneous fertilizer application during potato planting.

I - ridge former; II - spreader; III - ridge coverer 1 - stand; 2 - loosener; 3, 4 - hillers; 5 - fertilizer tube; 6 - bar; 7, 8 - furrow coverer; 9 - ring; 10 - slat

The proposed unit operates as follows. When the furrow opener is lowered into the soil, the share and the attached blade interact with the ground, opening up the potato ridge. Fertilizers are then delivered through the fertilizer tube to this area, where they come into contact with the slats of the freely rotating ring of the spreader and are distributed across the width of the potato ridge. The spreader's rotation with the

slats is driven by the engagement of the slats with the bottom of the furrow, which helps embed the mineral fertilizer particles into various layers of the potato ridge, thereby improving their distribution throughout the ridge volume. After this, the spreader slats throw a layer of soil over the fertilizer, forming a covering layer of 2-3 cm. Then, the furrow opener's covering slats push soil from the edges of the furrow over the mineral fertilizer, creating a 2-3 cm thick layer. Potato seeds are then delivered through the seed tube onto this soil layer. Next, the furrow-forming disc covers the seeds with soil and shapes the potato ridges. As a result, fertilizer distribution across the width and depth of the potato ridge is improved.

Determination of the impact interaction of mineral fertilizer granules with the slats: To determine the design parameters of the proposed furrow opener, a schematic diagram of the slat speed on the ring is used (Figure 5).

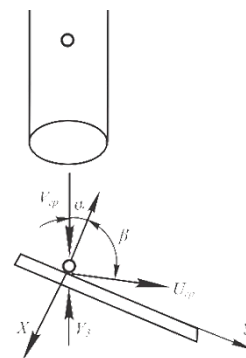


Figure 5. Diagram for determining the impact interaction of granules with the slats.

The velocity of the ring slat is determined taking into account the forward speed of the potato planter and the depth of the slat's penetration into the soil.

$$V_{II} = \frac{V_M}{r_{cp}} \cdot r_{II} \quad (1)$$

where V_{II} - speed of the bar, m/s; V_M - working speed of the machine, m/s; r_{cp} - average radius of the embedded bar, m; r_{II} - radius of the bar, m.

In addition, the interaction speed of mineral fertilizers with the bars is determined by the height of the fertilizer granules' fall:

$$V_{TP} = \sqrt{2 \cdot g \cdot h} \quad (2)$$

V_{TP} - speed of mineral fertilizer granules during their fall in the fertilizer tube, m/s; h - fall height (length of the fertilizer tube), m; g - acceleration due to gravity, m/s².

Taking this into account, let us consider the impact interaction of mineral fertilizer granules with the bars after falling from the fertilizer tube (Figure 5).

Before the interaction of the bar with the mineral fertilizer granule, the velocity is composed of the granule speed V_{TP} and the bar speed V_{II} .

$$V_1 = V_{TP} + V_{II} \quad (3)$$

Let's determine the velocity projections onto the coordinate axes x and y .

$$\begin{cases} V_{1x} = V_1 \cdot \cos \alpha \\ V_{1y} = V_1 \cdot \sin \alpha \end{cases} \quad (4)$$

where V_{1x} - normal component of the granule velocity at the beginning of the impact, m/s; V_{1y} - tangential component of the granule velocity at the beginning of the impact, m/s; α - angle of collision of the granule with the bars (angle of fall), degrees. The impact impulse, in the absence of friction force, is perpendicular to the surface of the bar, i.e.:

$$m \cdot U_1 - m \cdot V_1 = S_{yII} \quad (5)$$

where U_1 - velocity of the granule at the end of the impact, m/s; m - mass of the granule, kg; S_{yII} - impact impulse, kg m/s. Projection of equation (6) in the tangential direction:

$$m \cdot U_{1y} - m \cdot V_{1y} = 0 \quad (6)$$

or

$$U_{1y} = V_{1y} \quad (7)$$

Taking equation (4) into account, we can write:

$$U_{1y} = V_1 \cdot \sin \alpha \quad (8)$$

where U_{1y} - tangential component of the granule's velocity at the end of the impact, m/s;

The impact process occurs in 2 stages. In the first stage, the granule undergoes deformation; in the second stage, partial recovery of the granule occurs — the ratio of the impact impulses of these stages is characterized by the coefficient of restitution.

$$U_{1x} = -k \cdot V_{1x} \quad (9)$$

Where U_{1x} - normal component of the granule's velocity at the end of the impact, m/s; k - coefficient of restitution of the mineral fertilizer granule. Then, the projection of impulse equation (9) onto the x -axis, taking equation (4) into account, is as follows:

$$U_{1x} = -k \cdot V_1 \cdot \cos \alpha \quad (10)$$

The expression for determining the reflection angle of the fertilizer granules β can be written as follows:

$$\tan \beta = \frac{U_{1x}}{V_{1y}} \quad (11)$$

where β - rebound angle of the granule from the surface of the bar, degrees. Taking expressions (8) and (10) into account, we have:

$$\tan \beta = \frac{\tan \alpha}{k} \quad (12)$$

Let us determine the total velocity of the granule after rebounding from the bar.

$$U_1 = \frac{U_{1x}}{\cos \beta} \quad (13)$$

Substituting expressions (8) and (10), we obtain:

$$U_1 = \frac{-k \cdot V_1 \cdot \cos \alpha}{\cos \beta} \quad (14)$$

Taking into account the magnitude and direction of the granule's velocity after rebound, we determine the distance and trajectory of the granule's flight (Figure 6).

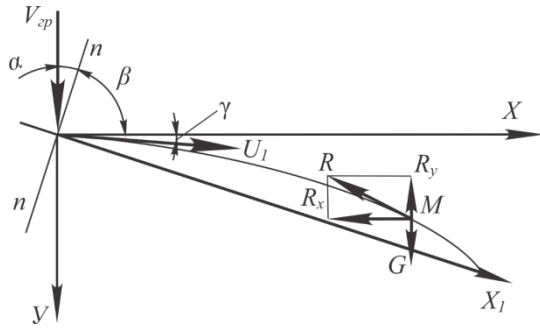


Figure 6. Calculation diagram for determining the trajectory of the granule after impact interaction.

The value of the rebound angle γ is determined by the following expression:

$$\gamma = 90^\circ - (\alpha + \beta) \quad (15)$$

where γ - angle of the granule's motion direction after rebound, degrees;

Since after the collision the granule moves in free flight, gravity force G and resistance force R are applied to it. Then, the basic law of motion is written as follows:

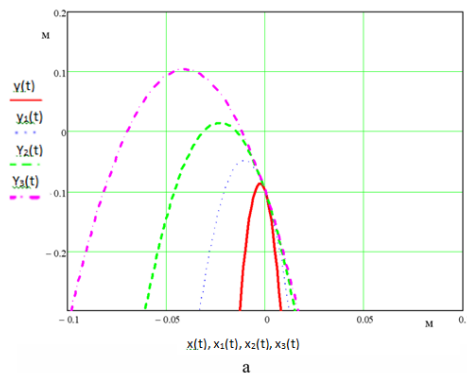
$$m \cdot a = G \quad (16)$$

where g - acceleration of the granule, m/s^2 ; G - weight of the granule ($G = m \cdot g$), N;

Let us project expression (16) onto the x and y coordinate axes (Figure 7).

$$\begin{cases} m \cdot \frac{d^2x}{dt^2} = 0 \\ m \cdot \frac{d^2y}{dt^2} = m \cdot g \end{cases} \quad (17)$$

Let us transform the system of equations (17) by dividing by m , we get:



a - direction of granule movement to the left, b - direction of granule movement to the right

Figure 7. Trajectory of fertilizer granules falling to the bottom of the furrow.

$$\begin{cases} \frac{d^2x}{dt^2} = 0 \\ \frac{d^2y}{dt^2} = g; \end{cases} \quad (18)$$

To solve this differential equation, we determine the initial condition corresponding to the equation for the variable x .

Initial conditions:

$$\text{At } t = 0, U_x' = U_1 \cdot \cos \gamma$$

Then: $dx/dt = C_1$; $dx/dt = U_1 \cdot \cos \gamma$

We obtain: $x = t \cdot U_1 \cdot \cos \gamma + C_2$

In this case, if $t = 0$, then $x = X_0$

X_0 - constant.

$$X = t \cdot U_1 \cos \gamma + X_0 \quad (19)$$

We obtain:

$$x = X_0 + t \cdot U_1 \cdot \cos \gamma$$

As with the variable y from the system of equations (17), we determine it using the initial conditions, i.e.:

$$\frac{d^2y}{dt^2} = g$$

At $t = 0, U_y' = U_1 \cdot \sin \gamma$

Then $C_1 = U_1 \cdot \sin \gamma$

So, In this equation, at $t = 0, y = y_0$

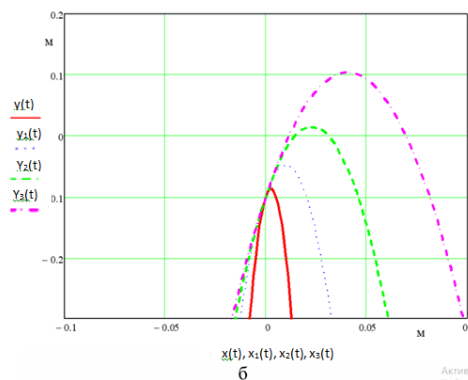
We have: $y_0 = 0 + 0 + C_2$

Thus, $C_2 = y_0$

Then:

$$y = y_0 + U_1 \cdot t \cdot \sin \gamma - (g \cdot t^2)/2 \quad (20)$$

Using the solutions from expressions (19) and (20), we will plot the trajectory of the granule's flight after the collision with the bars in the Mathcad program (Figure 6).



Analysis of Figure 6 shows that the use of a scatterer with oppositely directed bars allows for the distribution of mineral fertilizers across the width of the soil ridge.

An important factor influencing the rebound of granules from oppositely directed bars is the initial velocity of the granule.

The varying initial velocity of the granules is ensured by the corrugated fertilizer tube, which contributes to the distribution of solid mineral fertilizer granules across the width of the ridge.

In addition, the use of teeth with positive and negative inclination angles allows granules to be distributed on both sides of the scatterer.

Modeling the rebound distance made it possible to determine that the rational parameters are:

- 1) initial velocity of granules: 1.5...3.5 m/s;
- 2) tooth inclination angle: 5...60°;
- 3) tooth height at the moment of collision: 0.15 m.

To determine the efficiency of the new design of the unit, agrotechnical tests were conducted in 2025 in the fields of farmer enterprises in the Namangan region.

The test results showed that using the new working body for fertilizer application increased the potato yield by 4 centners per hectare compared to the existing technology.

The productivity of the unit increased by 1.4 times, and fuel consumption decreased by 1.2 times.

5. Conclusions

As a result of the conducted research, the efficiency of the new design of the opener equipped with a scatterer has been substantiated.

The scatterer is made in the form of a freely rotating rim with oppositely directed bars.

Thanks to this, it improves the distribution of fertilizers within the volume of the potato ridge in the root zone of the potato plant and contributes to an increase in potato yield.

The opener for subsurface application of mineral fertilizers must include a tine, a fertilizer tube, and a hiller equipped with a scatterer in the form of a freely rotating drum with oppositely directed bars.

In the course of theoretical studies, it was found that the use of a scatterer in the form of a rim with bars makes it possible to ensure the distribution of mineral fertilizer granules across the width of the ridge.

Abbreviations

V_{Π}	Speed of the Bar
V_M	Working Speed of the Machine
r_{cp}	Average Radius of the Embedded Bar
V_{rp}	Speed of Mineral Fertilizer Granules During Their Fall in the Fertilizer Tube

h	Fall Height (Length of the Fertilizer Tube)
g	Acceleration Due to Gravity

Author Contributions

Nabijon Boyboyev: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization

Teterin Vladimir: Conceptualization, Data curation, Formal Analysis, Methodology, Project administration, Resources, Supervision, Validation, Visualization

Lipatov Nikolay: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Resources, Software, Validation, Writing - original draft, Writing - review & editing

Komilov Nematilla: Conceptualization, Data curation, Methodology, Project administration, Resources, Visualization, Writing - original draft

Shukurjon Gulomov: Funding acquisition, Investigation, Resources, Visualization, Writing - original draft, Writing - review & editing

Conflicts of Interest

The authors declare no conflicts of interest.

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Biography



Nabijon Bayboboev is a highly respected Doctor of Technical Sciences and a professor, renowned for his extensive contributions to the field. He has conducted extensive research in the field of agricultural machinery, particularly in fertilizer application and potato cultivation technologies. Currently, he

works as a professor at the Department of Agricultural Mechanization at the Namangan State Technical University. He is also the chairman of the specialized academic council for doctoral dissertations in technical sciences. Bayboboev is the author of more than 100 scientific publications, including monographs, articles, and teaching manuals. He holds several patents for inventions that have been practically implemented in Uzbekistan's agricultural sector.

Teterin Vladimir is a researcher in the field of agricultural mechanization. In 2016, he earned his PhD (Candidate of Technical Sciences) at the Ryazan State Agrotechnological

University named after P.A. Kostychev. His dissertation focused on improving the technology and design of baler-collectors for harvesting stem crops with humate treatment. His scientific interests include the development and optimization of agricultural machinery for increasing efficiency and productivity in crop farming.



Lipatov Nikolay is a Russian agricultural entrepreneur from the Republic of Tatarstan. He founded and managed a peasant (farmer) enterprise starting in 2006, officially registered in the Russian Small and Medium Enterprise (SME) Registry. His farming activities included grain, legume, oilseed, and vegetable cultivation, along with livestock farming such as sheep, poultry, and beekeeping.



Komilov Nematilla is a respected PhD-qualified associate professor at the Namangan State Technical University, with specialized expertise in agricultural mechanization—particularly in soil tillage and fertilizer application technologies. His impactful work in both theoretical and applied research supports ongoing innovations in Uzbekistan's mechanized agriculture sector.

Shukurjon Gulomov is currently student an PhD. at the Namangan State Technical University in Uzbekistan. His academic focus is on post-harvest processing technology and the drying of vegetables. He co-authored the study "Investigation of Vegetable Drying Methods" with S.T. Tursunov, published on April 12, 2021, in the journal Food Technology.

Research Field

Nabijon Bayboboev: Agricultural mechanization, design of fertilizer application systems, potato harvesting technologies, development of resource-efficient machinery for soil cultivation.

Teterin Vladimir: Mechanization of harvesting processes, baler-collector design, humate-treated forage harvesting technologies, optimization of machine parameters for crop handling.

Lipatov Nikolay: Practical agricultural production, crop and livestock management, implementation of modern farming methods in small and mid-scale farms (entrepreneurial agriculture).

Komilov Nematilla: Soil tillage mechanization, fertilizer distribution systems, theoretical and experimental studies of rotary and disk-based working tools, kinematics of granular fertilizer flow.

Shukurjon Gulomov: Post-harvest processing, vegetable drying methods, food technology, optimization of drying parameters for quality preservation in agricultural products.