



SUBSTANTIATION OF THE PARAMETERS OF A DOSING MECHANISM FOR GRANULAR FERTILIZER APPLICATION DURING POTATO PLANTING

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Abstract. Based on the analysis of fertilizer consumption rates for potato cultivation, a new design of a dosing coil-type device has been proposed for conditionally discrete application of granular mineral fertilizers into potato nests. The structural and kinematic parameters of this device have been substantiated. Using the developed theoretical models, the limiting values of the rotation frequency were determined based on the condition of groove filling with fertilizers. The law of particle motion in the fertilizer tube was established, which made it possible to determine the time it takes for a particle to fall to the bottom of the furrow. This, in turn, allowed for determining the lead angle of the fertilizer discharge phase relative to the phase of potato tuber release by the planting mechanism. The obtained parameter values made it possible to synchronize these two devices and increase the efficiency of the potato planting technological process.

Key words: granular fertilizers, seeds, potatoes, planting pitch, potato planting machine, seed tube, unit, kinematic parameters, speed, process, transportation, experiment.

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1. INTRODUCTION

Achieving high yields of agricultural crops largely depends on the proper observance of cultivation technology, which represents one of the key factors in crop production. Among the most critical technological operations in potato cultivation is planting combined with the simultaneous application of mineral fertilizers. The amount of fertilizer applied and its spatial distribution have a significant impact on plant development. Therefore, the design of dosing mechanisms and their synchronization with the main units of potato planters is an important task for agricultural machinery engineers.

It often occurs that fertilizers are applied in accordance with the recommended rate per hectare, yet high yields are not achieved under otherwise equal conditions. The cause may lie in the improper localization of fertilizers within the planting row. For instance, most fertilizer dosing devices provide uniform distribution along the row; however, greater efficiency could be obtained if fertilizers were localized near each potato nest. This approach ensures a more uniform nutrient supply to each plant.

To implement the concept of conditionally discrete application of solid mineral fertilizers, it is necessary to develop a dosing device and integrate it into the design of the potato planting machine.

2. REVIEW OF RECENT RESEARCH AND PUBLICATIONS

Industrial manufacturers produce a variety of dosing devices for solid granular mineral fertilizers. In potato planters, the devices most commonly employed are fluted-roller, peg (pin-type), or fluted-roller-peg hybrid mechanisms [13, 14, 16, 17, 20, 24]. These mechanisms are intended to meter fertilizers and ensure their uniform distribution along the row during potato planting.

Conversely, numerous studies have focused on maintaining the planting pitch (in-row spacing) of seed tubers [2, 4, 5, 6, 7, 8, 10, 15, 18, 19, 21, 22] and on determining the required fertilizer rates and nutrient forms to maximize yield [1, 9, 11, 12]. However, the issues of localized placement of granular fertilizers within the nutrient zone of the seed-tuber site, as well as the specific mechanisms and the dosing and application process itself, have not yet been sufficiently addressed. This gap is particularly evident for potato planters designed for smallholder and farm-scale operations, where compact, synchronized, and precisely localized fertilizer delivery systems are critically needed.

Therefore, the development or improvement of fertilizer metering mechanisms and the fertilizer conveying process, which together ensure quasi-discrete at-planting fertilization of potatoes – aimed at increasing the crop yield – is a relevant issue for agro-industrial production and agricultural machinery engineering.

To analyze recommended application rates of granular mineral fertilizers for potato cultivation and, on this basis, to design a fluted-roller dosing device and investigate its operation with the capability to synchronize with the planting pitch and to discretely place fertilizer into the target nutrient zone of the seed tuber.

3. PRESENTATION OF THE MAIN MATERIAL

Before designing any unit or mechanism, it is essential to correctly define the initial design parameters and to clearly understand the nature of the working process [3]. In a two-row potato planter, according to the technical specification, the design includes the capability for fertilizer application during planting. Consequently, the first question that arises concerns the performance of the dosing device, that is, the rate of fertilizer application it must ensure. The answer to this lies in the crop cultivation technology, while from a technical point of view, it depends on the structural and kinematic parameters of the device.

Let us consider the typical potato cultivation technologies used in household and small farm plots, for which this potato planting machine has been developed. According to the literature [23], the recommended fertilizer application rate per 100 m² for «poor» soils and in cases of insufficient organic fertilization should have the following distribution (Figs. 1 and 2).

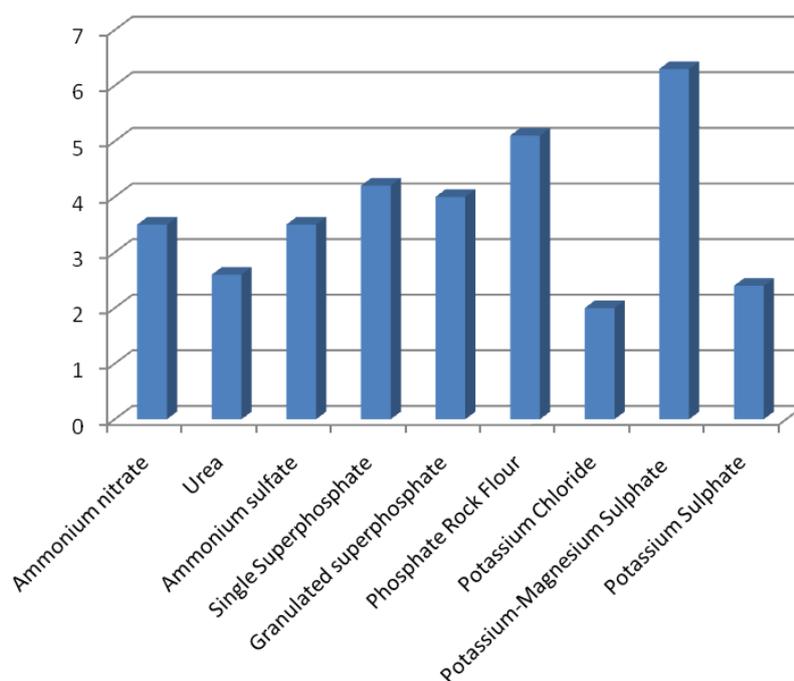


Figure 1. Fertilizer application rates for potato cultivation by type of fertilizer

However, in practical applications, granulated complex mixed fertilizers are most commonly used, such as nitroammophoska, ammonium phosphate (N:P), and nitrophos (N:P) (Fig. 2).

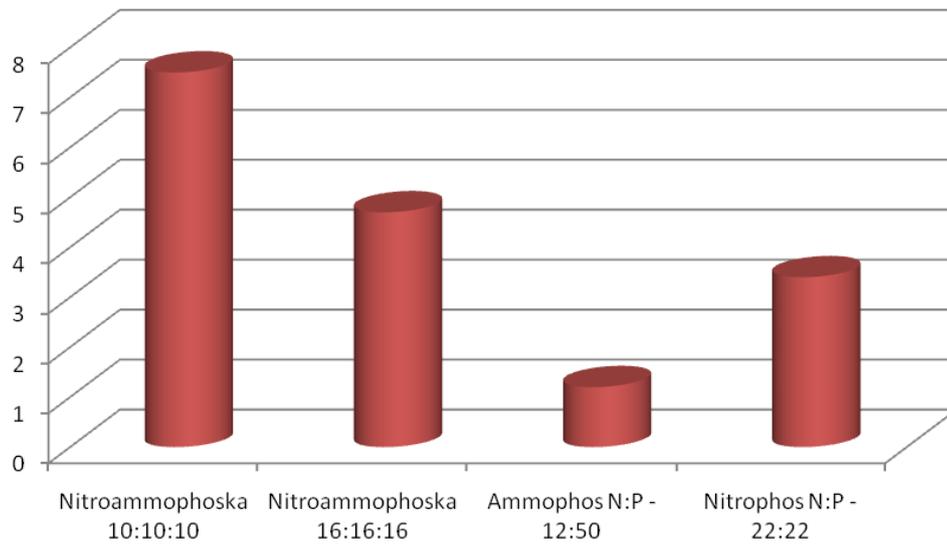


Figure 2. Application rates of complex mixed fertilizers

On the histograms (Figs. 1 and 2), the maximum fertilizer application rates are presented. These values are used in the design process to ensure that the dosing mechanism provides sufficient capacity for the highest required throughput. Next, the fertilizer rate specified per 100 m² of potato bed must be converted to the rate corresponding to a single planting row, for which the row spacing plays a crucial role: a wider spacing implies a higher rate per row, whereas a narrower spacing requires a lower rate. A second important criterion is the need to apply fertilizer in a quasi-discrete manner directly into the root feeding zone of the plant and to synchronize this process with the potato planting step. This can be achieved by aligning the number of planting cups (cells) in the potato planting mechanism with the number of cavities (grooves) in the fertilizer dosing device.

In the study [2], the operational principle of the potato planting mechanism of the developed machine is described, where the number of planting cups equals 14. This allows us to adopt the same or a multiple number of grooves in the fertilizer dosing rotor. Based on the preliminary analysis of literature sources and practical planter designs, the fluted-roller (coil-type) dosing mechanism is the most rational and structurally simple solution. Consequently, it is necessary to calculate the volume of a single groove, assuming a constant transmission ratio between the potato planting unit and the fertilizer dosing rotor.

To determine this groove volume, the following dependence can be used

$$V_1 = \frac{Q_s l_{m \max} l_{p \max} i_p}{S_p \rho_{\min}}, \quad (1)$$

where Q_s – fertilizer application rate for the specified area, kg/ha;

$l_{m \max}$ – maximum row spacing, m;

$l_{p \max}$ – maximum planting pitch, m;

S_p – designated planting area, m²;

ρ_{\min} – bulk density of the granular mineral fertilizer, kg/m³;

i_p – transmission ratio of the drive mechanism.

The required groove volume of the fluted roller is determined by the groove profile and its axial length. In addition, the roller must incorporate 14 grooves (or a multiple thereof) to synchronize with the planting unit. The overall dimensions of the roller are also a constraining factor.

Based on preliminary calculations, the following design assumptions are adopted: roller diameter 130 mm, number of grooves 7, and effective (working) length 80 mm. Considering a single groove pitch on the roller, the groove width ratio across the cylindrical surface is taken as 0.4 : 0.6.

The dosing device is kinematically linked to the planting mechanism; its rotational frequency is twice that of the planter’s metering unit. Using the Mathcad 14 application, the rotational speed of the fertilizer dosing roller can be expressed as a function of the planting pitch and the forward speed of the machine, illustrating how the dosing frequency varies with operating parameters.

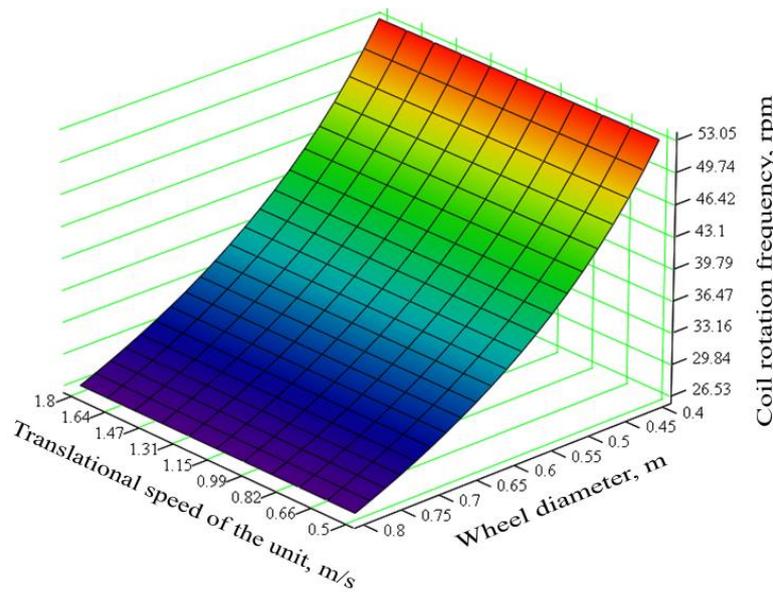


Figure 3. Variation of the fluted roller rotation frequency depending on the planting pitch and the forward speed of the unit

To analyze the behavior of a fertilizer granule inside the groove of the fluted roller, the maximum rotational speed of the roller under the specified operating conditions is considered. The force interaction diagram for an individual fertilizer granule located within the groove is presented in Fig. 4.

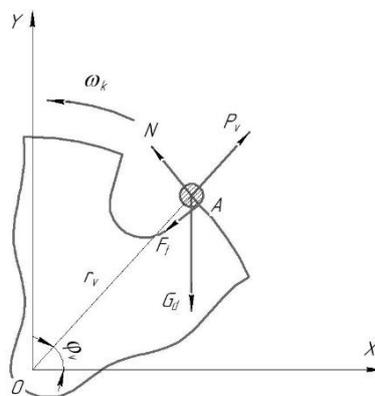


Figure 4. Diagram of forces acting on a fertilizer granule during groove filling

From the equilibrium condition and by projecting all acting forces onto the line of action of the centrifugal force (neglecting the groove's inclination angle), we obtain

$$-F_t - G_d \sin \varphi_v + P_v = 0, \tag{2}$$

where F_t – friction force, N;

G_d – weight of the fertilizer granule, N;

φ_v – rotation angle of the fluted roller, rad;

P_v – centrifugal force, N,

expanding expression (2), we can write

$$-Nf_t - m_d g \sin \varphi_v + m_d \omega_k^2 r_v = 0, \tag{3}$$

where N – normal reaction force, $N = G_d \cdot \cos \varphi_v$.

From expression (3), we can determine the allowable angular velocity of the roller:

$$\omega_k = \sqrt{\frac{g(\cos \varphi_v f_t + \sin \varphi_v)}{r_v}}, \tag{4}$$

We perform an analysis of the obtained dependence (4) with respect to the rotation angle of the fluted roller in order to determine its position that prevents granules from entering the groove. The graphical dependence is presented in relation to the rotation frequency of the roller within the range of groove positions from 30° to 120°, Fig. 5.

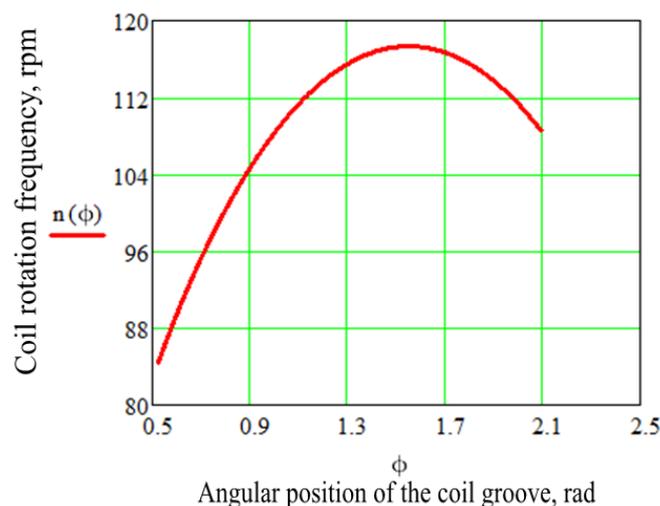


Figure 5. Limiting values of the fluted roller rotation frequency

According to the analysis of the graphical dependence (Fig. 5), it is evident that the obtained values of the permissible angular velocity of the fluted roller, determined within the range of rotation angles corresponding to the groove-filling phase, significantly exceed (by 2.1 times) the operating frequency values ($n_{k \max} = 39.3 \text{ rpm}$) required to ensure the specified maximum fertilizer application rate. This indicates that during the operation of the fluted-roller dosing mechanism, its grooves will be properly filled with granules and will effectively transport them to the discharge port leading into the fertilizer tube.

Furthermore, this factor allows us to adopt the operating frequency of the fluted roller determined from the fertilizer application rate calculation – as the basis for determining the initial velocity of granule ejection into the fertilizer tube. To determine the initial velocity of the granule as it enters the fertilizer tube, we also use the equilibrium condition of a particle located in the roller groove at the discharge port, where the fertilizer tube is attached. The computational model assumes that the granule is pressed against the groove wall by a force equal to its own weight. This assumption represents the most critical case of interaction between the fertilizer granules and the groove surface (the case of physical jamming of granules is not considered, as it is atypical). Therefore, during the rotation of the roller, the fertilizer granule is subjected to the same forces as in the previous case: friction, gravity, and centrifugal force.

The condition for the granule to fall out of the groove can be expressed as

$$\overline{P}_v + \overline{G}_d \geq \overline{F}_t. \quad (5)$$

Projecting the acting forces onto the vertical coordinate axis, we obtain the following expression describing the equilibrium condition, where the angle

$$P_v \sin \varphi_v + G_d = F_t, \quad (6)$$

where φ_v – is the angle defining the position of the granule at the moment it leaves the groove; it is measured from the horizontal coordinate axis counterclockwise.

A simple analysis shows that the particle will fall out of the groove when it is in the lower vertical position, even without the influence of centrifugal force, that is, under the action of its own weight only. This indicates that no special conditions are required for granules to fall into the fertilizer tube; therefore, the operating rotational frequencies of the fluted roller will only enhance this effect. Consequently, for calculating the initial ejection velocity of the granule from the roller groove of the dosing device, it is reasonable to use the operating frequencies of the roller corresponding to the specified potato planting steps. Accordingly, the calculation should be based on the value of the centrifugal force arising under normal operating conditions of the roller rotation. The frictional force of the granule against the groove wall is fully compensated by the gravitational force acting on the granule itself.

Then, the initial velocity of the particle ejected from the groove of the fluted roller is determined based on Newton's second law. In this case, the following relationship is obtained:

$$P_v = m_d a_r \text{ or } m_d \omega_k^2 r_v = m_d a_r, \quad (7)$$

where a_r – acceleration of the granule in the radial direction, m/s^2 .

Hence, this acceleration can be expressed as

$$a_r = \omega_k^2 r_v, \quad (8)$$

Now it is necessary to determine the radial velocity of the particle from the obtained acceleration. If the fertilizer granule starts its motion from a point with the radial coordinate r_0 and reaches the point r_v , which corresponds to the edge of the groove, then its radial velocity can be found from the following relation

$$\mathcal{G}_{r_v}^2 - \mathcal{G}_{r_0}^2 = 2 \int_{r_0}^{r_v} a_r dr . \quad (9)$$

However, in most cases, the initial radial velocity of the particle in the groove is very small or $v_{r_0} \approx 0$, then

$$\mathcal{G}_{r_v} = \sqrt{2 \int_{r_0}^{r_v} \omega_k^2 r_v dr} . \quad (10)$$

Since the unit moves across the field at a constant translational speed, and the dosing device is kinematically linked to the planting mechanism, the angular velocity of the fluted roller is constant. Then we have

$$\mathcal{G}_{r_v} = \sqrt{2 \omega_k^2 \int_{r_0}^{r_v} r_v dr} = \sqrt{\omega_k^2 (r_v^2 - r_0^2)} = \omega_k \sqrt{r_v^2 - r_0^2} . \quad (11)$$

The total velocity of the particle at the moment it leaves the groove is the geometric sum of the circumferential \mathcal{G}_t and radial velocities

$$\mathcal{G}_{\text{total}} = \sqrt{\mathcal{G}_{r_v}^2 + \mathcal{G}_t^2} = \omega_k \sqrt{2r_v^2 - r_0^2} . \quad (12)$$

Next, it is important to determine the time required for the particle to travel along the fertilizer tube. This parameter is necessary to achieve synchronized transport of both fertilizers and potatoes to the bottom of the furrow. From a technological standpoint, we will ensure that the fertilizers are discharged beneath the potato nest over a width approximately in the ratio of 0.4:0.6 relative to the planting pitch and about 20 mm below the bottom of the potato bed. This will constitute quasi-discrete application into the target zone rather than continuous fertilizer application along the row.

To determine the time of the particle's fall through the fertilizer tube, we compose the following equation

$$\frac{d\mathcal{G}}{dt} = g \sin \theta - \mu_t g \cos \theta - \frac{\rho_p C_d A}{2m_d} \mathcal{G}^2 , \quad (13)$$

where g – acceleration due to gravity, m/s²,

θ – angle of the fertilizer tube relative to the horizontal, rad;

μ_t – coefficient characterizing dry friction against the inner wall of the fertilizer tube;

C_d – coefficient of air resistance acting on the moving granule;

ρ_p – air density, kg/m³;

A – area of the granule (m²) exposed to the airflow (midship cross-section), $A = \frac{\pi d^2}{4}$,

here d – diameter of the idealized granule, assumed spherical, m;

m_d – mass of the granule, $m_d = \rho_{\text{min}} \frac{\pi d^3}{6}$, kg.

Omitting the intermediate derivations, we obtain the solution for the velocity of the particle moving in the fertilizer tube

$$g(t) = \sqrt{\frac{a}{b}} \tanh(\sqrt{ab} t + \xi_0), \quad (14)$$

where the following symbols are used: $a = g(\sin \theta - \mu_t \cos \theta)$; $b = \frac{\rho_p C_d A}{2m_d}$,

where $\xi_0 = \operatorname{artanh}\left(g_0 \sqrt{\frac{b}{a}}\right)$.

The relationship with the distance traveled is expressed as

$$s(t) = \frac{1}{b} \left[\ln \cosh(\sqrt{ab} t + \xi_0) - \ln \cosh(\xi_0) \right]. \quad (15)$$

Then, the time required for the fertilizer granule to pass through the fertilizer tube is determined by the expression

$$t = \frac{1}{\sqrt{ab}} \left[\operatorname{ar} \cosh(e^{bL} \cosh \xi_0) - \xi_0 \right], \quad (16)$$

where L – height of installation of the seed drill, m.

When modeling a real numerical experiment, the following initial data were used.

For the fertilizer dosing device: $L = 1$ m; $r_v = 0.065$ m; $\omega_k = 3.087$ rad/s; $\rho_{\min} = 1200$ kg/m³; $\rho_p = 1.2$ kg/m³; $\mu_t = 0.0015$; $C_d = 0.47$; $d = 0.006$ m; $\theta = 80^\circ$. Then, according to dependence (16), the time required for the fertilizer granule to pass through the fertilizer tube is $t = 0.452$ s.

For the potato planting mechanism, a similar theoretical approach is applied to determine the time required for a potato tuber to pass through the seed tube. The calculation is carried out using the following input data: $L_k = 0.9$ m; $r_{vk} = 0.226$ m; $\omega_{kk} = 1.547$ rad/s; $\rho_{\min k} = 1150$ kg/m³; $\rho_p = 1.2$ kg/m³; $\mu_t = 0.0015$; $C_d = 0.47$; $d_k = 0.06$ m; $\theta_k = 80^\circ$. Then, according to dependence (16), the time required for the potato tuber to pass through the seed tube is $t_k = 0.424$ s.

According to the results of the calculations, it is evident that the travel time of the fertilizer granules and the potato tubers through their respective tubes differs. This means that, at a constant forward speed of the machine, their deposition at the bottom of the furrow will also occur at different times. Therefore, this factor must be taken into account to ensure synchronous operation of the planting and dosing mechanisms.

Recall that the task was formulated so that the mineral fertilizers are distributed beneath the potato nest approximately in the ratio 0.4:0.6 relative to the planting pitch. For example, if the planting pitch is 0.291 m and considering the design of the dosing roller, the fertilizer placement length should be 0.117 m. To synchronize the operation of the fluted-roller dosing unit and the planting mechanism, fertilizers must begin to be placed 0.059 m before the center of the nest. In addition, the delay in fertilizer transport relative to the transport of the potato tuber must be considered. For a travel speed of 1 m/s, this distance corresponds to 0.028 m.

It is also necessary to account for the structural distance between the fertilizer delivery tube and the seed tube, which equals 0.1 m. Taking into consideration the machine's speed, the rotation frequency of the dosing roller, and the mentioned distances, to achieve synchronization between the dosing and planting mechanisms, the phase of fertilizer discharge by the roller must be advanced by 33° relative to the phase of potato discharge by the planting device.

4. CONCLUSIONS

Based on the derived dependence (1), the design parameters of the dosing fluted roller were determined: number of grooves – 7; effective groove area – $290 \cdot 10^{-6} \text{ m}^2$; working length of the roller – 0.08 m.

A theoretical model was developed to establish the limiting angular velocities of the roller that ensure proper groove filling with fertilizer. A comparative analysis was conducted between these limiting values and the operating angular velocities corresponding to the required fertilizer application rate. It was found that the maximum operating angular velocity is 2.1 times lower than the minimum permissible value, which confirms the reliable filling of grooves with fertilizer granules.

According to the developed model, the travel time of fertilizer particles in the fertilizer tube and the travel time of seed potatoes in the seed tube were determined. Based on these results, a synchronization rationale was proposed for the coordinated operation of the fluted-roller dosing mechanism and the potato planting unit to achieve quasi-discrete fertilizer application beneath the potato nest.

When the phase of fertilizer discharge by the roller is advanced by 33° relative to the phase of tuber discharge by the planting device, both processes become synchronized. This ensures symmetrical placement of fertilizers relative to the center of the potato nest, with a distribution length equal to 0.4 of the planting pitch. This approach will increase the concentration of fertilizers in the potato nest, improve the nutritional efficiency of cultivated plants, and lead to a 10% increase in potato yields without increasing the amount of fertilizer applied to a given area.

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УДК 631.332.7

ОБҐРУНТУВАННЯ ПАРАМЕТРІВ ДОЗУЮЧОГО АПАРАТА ДЛЯ ПРИПОСАДКОВОГО ВНЕСЕННЯ ГРАНУЛЬОВАНИХ ДОБРИВ

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***Резюме.** Наведено результати теоретичних досліджень процесу дозування для припосадкового внесення гранульованих мінеральних добрив під картопляне ґніздо. На основі аналізу норм споживання добрив при вирощуванні картоплі розроблено катушковий дозуючий апарат, що забезпечує умовно дискретне внесення добрив у зону живлення рослини. Отримано аналітичну залежність для визначення об'єму жолобка катушки залежно від норми внесення добрив, ширини міжрядь, кроку посадки тощо. За*

результатами моделювання отримано такі параметри катушки: діаметр – 130 мм, кількість жолобків – 7, ефективна площа жолобка – $2,9 \cdot 10^{-4} \text{ м}^2$, робоча довжина – 0,08 м, передаточне число привода – 2. Показано, що граничні значення кутової швидкості катушки, отримані з умови заповнення жолобків гранулами добрив, перевищують робочі у 2,1 рази, звідки випливає, що процес заповнення відбувається надійно. Розроблено математичні моделі руху частинки добрива у тукопроводі та картоплі у насінепроводі, звідки визначено час проходження ними відстаней при транспортуванні їх цими технологічними трубопроводами до вкладання на дно борозни. За різницею часу транспортування гранул добрив та картоплин, а також із урахуванням положення початку висипання туків відносно до центру гнізда картоплі, конструктивного розміщення тукопроводу та насінепроводу встановлено, що для синхронізації дозуючого апарату добрив та картоплепосадкового апарату необхідно, щоб фаза викидання добрив випереджала фазу викидання картоплин на 33° . На основі цього досягається ефект умовно дискретного внесення добрив під картопляне гніздо розрахунковою протяжністю 0,4 від кроку посадки та симетрично розміщеного відносно центру гнізда. Таке конструктивне розроблення матиме значний технологічний ефект при вирощуванні картоплі, оскільки дозволить забезпечити оптимальні умови живлення кожного куща рослини, а це сприятиме підвищенню урожайності культури.

Ключові слова: гранульовані добрива, насіння, картопля, крок посадки, картоплесаджалка, насінепровід, агрегат, кінематичні параметри, швидкість, процес, транспортування, експеримент.