RESEARCH IN PROCESSES AND MACHINES FOR LOCAL STRIP APPLICATION OF MOISTURE-HOLDING ORGANIC FERTILIZERS

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Abstract. In Ukraine's territories, there is a potential for rapid growth in organic agricultural production, not only for the domestic market but also for the global market. However, achieving this requires a shift in plant production technologies and ensuring the production of necessary agricultural machinery to facilitate specific technological operations. Global climate change necessitates alterations in regional crop rotations due to reduced plant productivity, especially during the germination stage, where moisture requirements fluctuate. Conversely, the pursuit of maximum yields has led to intensified use of mineral fertilizers, contributing to ecological degradation and decreased soil fertility. Maintaining the balance of nutrients in the soil can be achieved by regular local application of moisture-retaining organic fertilizers in the range of 10-12 tons per hectare. These fertilizers should be derived from organic raw materials possessing a well-developed colloidal structure capable of gradual moisture accumulation and release. Proposed components for producing these fertilizers include sapropel with natural moisture content sourced from freshwater reservoirs. This study presents laboratory and field research results from experimental plots cultivating potatoes, vegetables and soybean, affirming the effectiveness of the proposed technology. The article also describes the construction of machines for local application of moisture-retaining organic fertilizers. A theoretical study of the interaction of organic fertilizer particles with the working body of such machines is presented, and the dimensions and rotation speed are substantiated.

Keywords: soil, fertility, organic fertilizers, sapropel, machinery, application.

Introduction

The global trend towards consuming organic produce is actively spreading. Military actions have had a negative impact on the development of organic farming, resulting in a reduction in the area dedicated to organic production in Ukraine from 1% to 0.6%. The national economic strategy aims to achieve no less than 3% of the total agricultural land area under organic production by 2030 [1]. However, these figures are significantly lower than the results achieved in many European Union countries.

The high productivity of modern agricultural production in Ukraine is mostly achieved through the application of increased doses of mineral fertilizers [2]. Organic fertilizers are practically not applied. There is a phenomenon known as soil degradation, which weakens the soil reproductive properties, erosion resistance, and resistance to chemical and technological influences [3-5]. The application of organic fertilizers is the best way to enrich the soil with organic matter, which can be transformed into humus, significantly enhancing its fertility. At the same time, humic and fulvic acids are synthesized in the soil, which have increased exchange capacity.

Furthermore, at present, achieving high crop yields of agricultural crops is significantly limited by the climate change in general and catastrophic decreases in soil moisture reserves, in particular. Climate zones are shifting to the North and West. Virtually all sown areas of agricultural crops in Ukraine have fallen into zones of risky agriculture [6].

The alternative to the lack of animal-origin organic fertilizers for many years has been considered to be sapropel. Analysis of existing research indicates that the impact of sapropel on soil fertility is significant and complex, as it is an environmentally clean organo-mineral raw material that enhances the soil structure and serves as a quality source of humus replenishment [7-9]. Due to the presence of humic substances in organic sapropel, which are characterized by radioprotective, accumulative, transport, regulatory, and physiological properties, sapropels are recommended for use in technogenically and radiation-contaminated areas [10; 11]. The potential of sapropels as an alternative source of organic matter for preserving and restoring soil fertility throughout Ukraine exceeds 91 million tons [10; 12].

At the same time, attention should be paid to the high moisture content of freshly extracted sapropel, which ranges from 92-98% for its organic type [13]. Commonly accepted technologies for further use of sapropel involve its dehydration to a moisture content of 60% [10]. Applying naturally moist sapropel at a rate of up to 10 tons per hectare in fields located within a distance of up to 20 km from the extraction site not only eliminates the need for dehydration costs but also contributes to the formation of an additional moisture reserve in the soil. It is evident that achieving this effect is possible through local application of sapropel, especially during its application under crops planted using wide-row planting methods. Furthermore, attention should be drawn to the moisture-absorbing properties of organic fertilizers based on sapropel. Studies [14] have indicated the possibility of producing briquettes based on sapropel to accumulate water for the long-term provision of moisture to plants, for example, in greenhouses.

Climate change, energy crisis, and soil degradation processes compel Ukrainian farmers to depart from classical farming systems and implement energy- and resource-saving systems: Mini-till, No-till, Strip-till, Verti-till [15-17]. Among these systems, the cultivation of crops using the Strip-till technology is gaining increasing popularity, which involves replacing the row method with strip planting with a row width of 45 cm. These trends pave the way for the local application of sapropel in its pure form or as part of manufactured organic fertilizers for crops planted using the row method. This solution is particularly relevant for soils of light mechanical composition that are directly adjacent to sapropel deposits [18, 19].

Devices for applying organic fertilizers are trailers or bodies with built-in working elements for distributing manure, peat, composts, mulch, and other materials over the surface of the field. The working elements of such machines are rotating beaters onto which various components in the form of blades, knives, and teeth are attached along a helical line for effective shredding of fertilizer components [20]. Machines for local application of organic fertilizers are practically non-existent.

The aim of our research was to determine the effect of the technology of local strip application of organic fertilizers based on naturally moist sapropel on the cultivation process of agricultural crops, as well as to develop a structural solution and justify the parameters of machinery to implement such technology.

Materials and methods

The effectiveness of forming nutrient zones in the form of strips using sapropel-based organic fertilizers for potato and onion cultivation was studied after autumn ploughing of the experimental plot. Organic fertilizers were applied in furrows with a cross-section of 20×20 cm and a length of 300 cm, with a distance of 100 cm between furrows. The following fertilizer variants were applied: a mixture of organic sapropel with straw from cereal crops with a moisture content of 10-12% (variant 1); a mixture of organic sapropel with softwood shavings with a moisture content of 30-35% (variant 2); organic sapropel alone (variant 3). The moisture content of sapropel in all variants was 95%, and the ratio between sapropel and the second component ranged from 8:1 by physical weight. The fertilizer layer in the soil was formed based on the application rate of 10 $tons \cdot ha^{-1}$. Strips of fertilizers for variants 1 and 2 were applied with triple replication, while variant 3 was applied with double replication. A total of 8 research variants were established. The applied organic components were covered with a layer of soil to the level of the field surface. The following spring after the fertilizers were applied, potatoes were planted with a row spacing of 50 cm, ensuring that the row axis was above the furrow where the fertilizers were applied. This allowed for the formation of unfertilized rows between the rows of potatoes located above the previously applied fertilizers. This scheme ensured obtaining control indicators. Onion planting was carried out using a similar scheme. To determine the effectiveness of the formed nutrient zones, potatoes and onions were harvested separately, and the yield was calculated accordingly.

Laboratory studies on the effect of naturally moist sapropel on soybean yield were conducted in a bulk channel where seven sections, each 45 cm wide, were formed using partitions. Soybeans of the Apollo variety were sown in the formed sections at a seeding rate of 120-140 $kg \cdot ha^{-1}$. In addition, conditions of both the conventional tillage system and Strip-Till were replicated in the sections. Different fertilization options were also applied: UAN N32 100 $kg \cdot ha^{-1}$; N45P45K45 (45 $kg \cdot ha^{-1}$ - N; 45 $kg \cdot ha^{-1}$ – P_2O5; 45 $kg \cdot ha^{-1}$ – K_2O); and 20 $tons \cdot ha^{-1}$ of naturally moist sapropel. One section served as a control, where no fertilization was applied. During the experiment, extreme moisture conditions were created by irrigating the sections three times during the entire vegetation period, with an irrigation rate of 10 mm of water for each research variant. Soybean pods were harvested separately from each section to determine the yield. Subsequently, the grains were separated and weighed.

For the experimental study of the effect of high-moisture organic fertilizers on soil moisture content, plastic containers were used into which soil, the specified organic fertilizers, and soil again were layered. The bottom layer consisted of soil, the middle layer of organic fertilizers, and the top layer also of soil. The thickness of each layer was 50 mm. A mixture of naturally moist sapropel with a moisture content of 92% and an organic filler were used as organic fertilizers. Wheat straw, wood sawdust and flax straw were used as fillers. In all experimental variants, the weight ratio between sapropel and the organic filler was 8:1. Two types of soil were used in the experiments based on their mechanical composition: sandy and clayey soils. Moisture measurements of each of the three layers formed in the container were conducted using the MG-44 soil moisture meter. During the experiment, one-time irrigation of the tested samples was carried out to simulate precipitation, with an amount of 20 mm.

Results and discussion

The results of field studies on the effectiveness of nutrient zones formed from organic fertilizers based on naturally moist sapropel are presented in Table 1, showing the average yields of Bella Rosa potatoes and Stuttgart Riesen onions.

Table 1

Average crop yields for different research variants

Crop	Variant 1	Variant 2	Variant 3	Control
Potatoes Bella Rosa	15.03 ± 0.78 $t \cdot ha^{-1}$	14.85 ± 1.03 $t \cdot ha^{-1}$	15.14 ± 0.95 $t \cdot ha^{-1}$	14.87 ± 0.91 $t \cdot ha^{-1}$
Onion Stuttgart Riesen	3.24 ± 0.28 $kg \cdot m^{-2}$	3.32 ± 0.36 $kg \cdot m^{-2}$	3.28 ± 0.41 $kg \cdot m^{-2}$	3.27 ± 0.33 $kg \cdot m^{-2}$

As a result of the laboratory study on the impact of fertilization systems under conditions of extreme moisture deficiency on soybean yield, we observed an increase relative to the control (no fertilization) in the case of using sapropel as a fertilizer at a rate of 20 $t \cdot ha^{-1}$ for both the Strip-Till system and the conventional tillage system (Table 2). This increase amounted to 9.8% and 9.4%, respectively. Additionally, a 10.0% increase was observed in the variant of fertilization with an NPK complex and the Strip-Till tillage system. In other study variants, there was a negative yield increase relative to the control. Visual observations also revealed that during the vegetation period, the most intensive plant growth occurred in the experimental variants where sapropel was applied, particularly using the Strip-Till technology. However, under conventional tillage and fertilization with UAN N32, soybean plants died after emergence and during the short vegetative period.

Table 2

Soybean yield value

Tillage system/fertilization	Strip-Till/UAN N32	Strip-Till/N45P45 K45	Conventional tillage/N45P45 K45	Strip-Till/ sapropel	Conventional tillage/sapropel	Control
Yield $t \cdot ha^{-1}$	2.54	4.82	3.36	4.81	4.79	4.38

The experimental study on the influence of organic fertilizers with increased moisture content on the soil moisture levels revealed a clear distribution of this parameter across the investigated soil layers in all study variants. Initially, the minimum moisture content was observed in the upper soil layer. The highest moisture values in the upper layer ranged from 22-23% at the beginning of the experiment to 12-14% before irrigation in the variants where sapropel + wheat straw was used for sandy soil and sapropel + flax straw for clayey soil (Fig. 1). Meanwhile, the moisture content in the upper layer in the remaining study variants ranged from 8-17% at the beginning of the experiment to 8-10% before irrigation.

The experiment results also indicate that moisture accumulated in the middle layer of organic fertilizers migrated most intensively to the lower layer in all study variants with clayey soil, where the moisture level alignment between the middle and lower layers occurred within the first 30 days of the experiment. In the study variants with organic fertilizers sapropel + flax straw and sapropel + wood sawdust, the moisture content of the lower layer became equal to that of the middle layer (Fig. 1). This trend persisted even after irrigation.

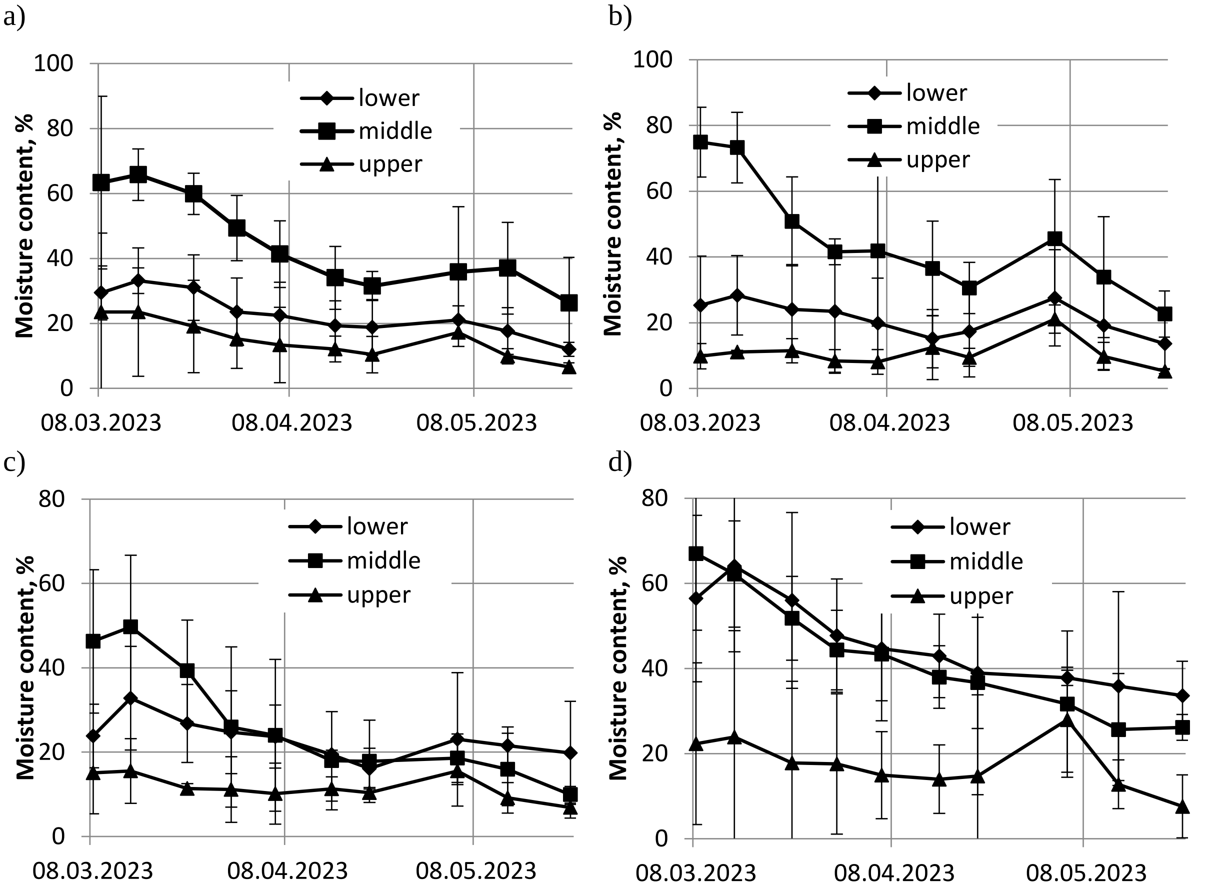

Fig. 1. **Change in the moisture content of soil layers and organic fertilizers according to the investigation time for the experimental variants:** a – sapropel + wheat straw and sandy soil; b – sapropel + wood sawdust and sandy soil; c – sapropel + wheat straw and clayey soil; d – sapropel + flax straw and clayey soil

In the study variants with sandy soil, the maximum moisture retention by the middle layer was observed when using sapropel + wood sawdust and sapropel + wheat straw as organic fertilizers. The difference in moisture between the middle and other two layers ranged from 10-12% in this case. In the study variants with sandy soil, the maximum amount of moisture added as a result of irrigation was also accumulated in the middle layer.

Analysis of the obtained experimental results indicates the inefficiency of incorporating organic fertilizers in the form of a mixture of sapropel with straw of cereal crops, softwood sawdust, and pure sapropel during the autumn period for subsequent spring planting of potatoes and onions. This is because a significant increase in the yield compared to the control is absent. Clearly, the effect can be achieved by pre-fermenting such fertilizers with the addition of nitrogen fertilizers to ensure a carbon-to-nitrogen ratio within the range of 1 to 20-30 [20].

At the same time, the results of the study on the influence of fertilization systems under conditions of extreme moisture deficiency on the soybean yield and the effect of organic fertilizers with increased moisture content on the moisture content of soil layers confirm the hypothesis of the possibility of creating a moisture-retaining nutrient layer of organic fertilizers based on sapropel and organic fillers such as straw of cereal crops, flax, wood sawdust, etc. A special effect is observed on light soils when these fertilizers are applied simultaneously with sowing of agricultural crops.

To implement the process of forming strips of fertilizers with increased moisture in the soil under the conditions of growing agricultural crops using wide-row planting (sowing) methods, it is possible to utilize modernized spreaders for organic fertilizers following the scheme outlined in [22]. To ensure the quality operation of the horizontal dosing meter of such a machine with organic fertilizers of increased moisture, it is necessary to provide self-cleaning of the blades. Such self-cleaning is possible when a particle comes off the working surface of the blade.

During the theoretical investigation of the interaction process between particles of high-moisture organic fertilizers and the blade of the dosing biter of the machine for local strip application of organic fertilizers, the methodology described in [23] was used. However, the movement of the material on the surface of the blade was considered as the motion of a particle with a mass m on a rough surface, taking into account adhesive forces. Additionally, it was assumed that the particle has a cubic shape with edges of size a.

In this case, the differential equations governing the motion of the organic fertilizer particles over the surface of the blade based on the scheme provided in [23] will take the following form:

$$\begin{cases} ma_x = G\,sin(180^0 - \psi + \omega_b t)\,sin\,\zeta - F_i\,sin\,\kappa\,sin\,\zeta - F_a\,sin\,\varsigma + F_{c2}\,sin\,\zeta; \\ ma_y = -G\,cos(180^0 - \psi + \omega_b t) + F_i\,cos\,\kappa - F_a\,cos\,\varsigma - F_{c1}; \\ ma_z = -G\,sin(180^0 - \psi + \omega_b t)\,cos\,\zeta + F_i\,sin\,\kappa\,cos\,\zeta - F_{c2}\,cos\,\zeta + N, \end{cases} \tag{1}$$

where m – mass of the particle mixture, kg;
a_x, a_y, a_z – represents the projections of the relative acceleration vector of the particle along the OX, OY, and OZ axes of the non-inertial coordinate system, m·s^{-2};
$G = mg$ – force of gravity (g – acceleration due to gravity), N;
F_i – centrifugal force of inertia, N;
F_a – tangential force of adhesion, N;
N – normal reaction of the supporting surface, N;
F_{c1}, F_{c2} – components of Coriolis force, N.

The centripetal force of inertia is equal to:

$$F_i = m\omega_b^2 R\,, \tag{2}$$

where ω_0 – angular velocity of the blade rotation, rad·s^{-1};
R – radius of the particle's rotary, m.

The tangential force of adhesion consists of:

$$F_a = sp_0 + pN\,, \tag{3}$$

where s – contact area between the particle of organic fertilizer and the surface of the blade, m^2;
p_0 – specific tangential adhesion force that arises in the absence of normal reaction of the supporting surface, N· m^{-2};
p – coefficient accounting for the specific tangential adhesion force arising in the presence of normal reaction of the supporting surface.

Accepting the assumption that the fertilizer particle has a cubic shape with an edge size of a and a mass:

$$m = sa\gamma\,, \tag{4}$$

where γ – volumetric mass, kg·m^{-3}.

Taking into account the formulas for the components of the Coriolis force F_{c1} and F_{c2} provided in [23], and the condition of no detachment of the particle from the surface during its movement on the blade, based on (1) – (4), we obtain:

$$\begin{cases} ma_x = mg\,sin(\psi + \omega_b t)\,sin\,\zeta - m\omega_b^2 R\,sin\,\kappa\,sin\,\zeta - \left[mp_0/a\gamma + pN\right] sin\,\varsigma + 2m\omega_b v_y\,sin\,\zeta; \\ ma_y = mg\,cos(\psi + \omega_b t) + m\omega_b^2 R\,cos\,\kappa - \left[mp_0/a\gamma + pN\right] cos\,\varsigma - 2m\omega_b v_x\,sin\,\zeta; \\ 0 = -mg\,sin(\psi + \omega_b t)\,cos\,\zeta + m\omega_b^2 R\,sin\,\kappa\,cos\,\zeta - 2m\omega_b v_y\,cos\,\zeta + N. \end{cases} \tag{5}$$

Taking into account the dependencies for determining $R sin\kappa$, $R cos\kappa$, $sin\varsigma$, $cos\varsigma$ provided in [23], and the relationship for the normal reaction of the blade N obtained from equation 3 of the system (5), we obtain:

$$\begin{cases} a_x = g\,sin(\psi+\omega_b t)sin\zeta - \omega_b^{\,2}\left(b/2-x\right)sin^2\zeta - \dfrac{v_x}{\sqrt{v_x^2+v_y^2}}\times \\ \times\left(\dfrac{p_0}{a\gamma}+p\left(g\,sin(\psi+\omega_b t)cos\zeta - \dfrac{\omega_b^{\,2}\left(b/2-x\right)}{2}sin2\zeta + 2\omega_b v_y\,cos\zeta\right)\right)+2\omega_b v_y\,sin\zeta; \\ a_y = g\,cos(\psi+\omega_b t)+\omega_b^{\,2}y - \dfrac{v_y}{\sqrt{v_x^2+v_y^2}}\times \\ \times\left(\dfrac{p_0}{a\gamma}+p\left(g\,sin(\psi+\omega_b t)cos\zeta - \dfrac{\omega_b^{\,2}\left(b/2-x\right)}{2}sin2\zeta + 2\omega_b v_y\,cos\zeta\right)\right)-2\omega_b v_x\,sin\zeta. \end{cases} \quad (6)$$

The system of nonlinear nonhomogeneous second-order differential equations with constant coefficients (6) was solved using the Rosenbrock numerical method, implemented in the Maple computational mathematics system. Based on the solution of system (6), the constructed trajectories are shown in Figure 2.

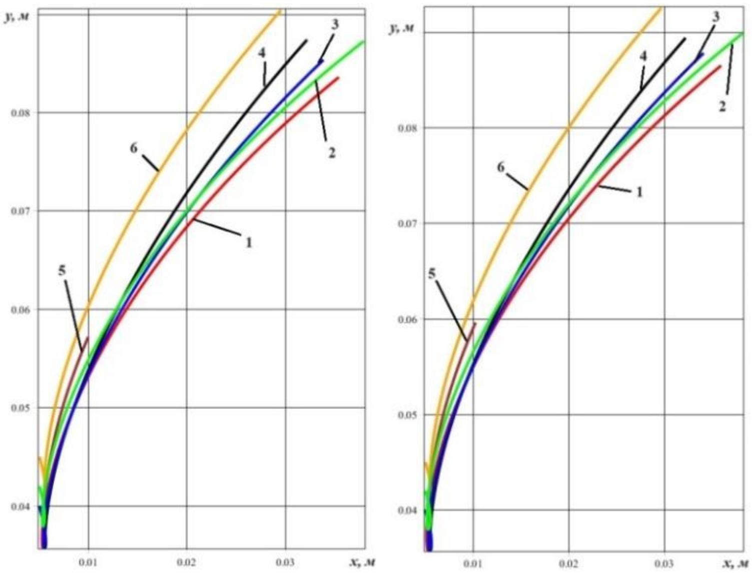

Fig. 2. **Fertilizer particle trajectories along the surface of the shovel with the widths of 25 mm (left) and 30 mm (right) as it rotates at a speed of 80 rad·s^{-1}:** 1 – ψ = 165º, ξ = 50º, a = 5 mm, y_0 = 40 mm; 2 – ψ = 175º, ξ = 50º, a = 5 mm, y_0 = 42 mm; 3 – ψ = 165º, ξ = 45º, a = 5 mm, y_0 = 40 mm; 4 – ψ = 165º, ξ = 40º, a = 5 mm, y_0 = 40 mm; 5 – ψ = 175º, ξ = 45º, a = 4 mm, y_0 = 40 mm; 6 – ψ = 165º, ξ = 45º, a = 4 mm, y_0 = 45 mm

Analysis of these graphs shows that the effective operation of the dosing blade, due to self-cleaning of the blades, will be ensured with their widths of 25-30 mm, an angle of inclination relative to the axis of rotation of the blade of 45-50 degrees, an initial distance from the axis of rotation to the point of fertilizer particle drop of 45 mm. In this case, the rotation speed of the blade should be 80 rad·s^{-1}, and the size of the fertilizer particles arriving on the blade should not be less than 5 mm.

Conclusions

1. To obtain high-quality fertilizers based on a mixture of sapropel with straw from cereal crops, softwood shavings, and pure sapropel, it is necessary to ferment them with the addition of nitrogen fertilizers to ensure a nitrogen-to-carbon ratio within the range of 1 to 20-30.
2. Positive effects on soybean yield under conditions of extreme moisture deficiency have been observed from the use of naturally moist sapropel and the moisture accumulation effect in the layer

of organic fertilizers with increased moisture content based on sapropel on sandy soil. These results create prerequisites for implementing a method of cultivating agricultural crops that involves creating strips of organic fertilizers with increased moisture content based on sapropel in the soil, combined with the simultaneous planting (sowing) of these crops. This method can be implemented based on a modernized organic fertilizer spreader.

3. Theoretical investigations into the operation of the dosing blade of a machine for localized application of organic fertilizers have revealed that self-cleaning of its blades from particles of high-moisture organic fertilizers will be ensured at a rotation speed of 80 $rad \cdot s^{-1}$, blade widths of 25-45 mm and an angle of their inclination relative to the axis of the blade of 45-50 degrees, with the initial distance from the axis of rotation to the point of fertilizer particle drop being 45 mm.

Author contributions

Conceptualization, V.D. and I.T.; methodology, V.D., I.T. and V.S; software, I.T. and R.Kh; validation, V.D. and R.Kh; investigation, I.T., V.D. and V.S.; data curation, V.D. and I.T.; writing – original draft preparation, I.T.; writing – review and editing, V.D. and V.S.; visualization, I.T. and R.Kh. All authors have read and agreed to the published version of the manuscript.

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