EXPERIMENTAL INVESTIGATION OF A MACHINE FOR LOCAL STRIP APPLICATION (MLSA) OF SAPROPEL-BASED ORGANIC FERTILIZER MIXTURES
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ЕКСПЕРИМЕНТАЛЬНІ ДОСЛІДЖЕННЯ МАШИНИ ДЛЯ ЛОКАЛЬНОГО СМУГОВОГО ВНЕСЕННЯ (МЛСВ) ОРГАНІЧНИХ ДОБРИВ НА ОСНОВІ САПРОПЕЛЮ

Igor TSIZ, Volodymyr DIDUKH, Serhiy KHOMYCH, Victor TARASYUK, Roman KHLOPETSKYI
Lutsk National Technical University / Ukraine
Tel: +38 050 147 28 44; E-mail: igor-71@ukr.net
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ABSTRACT
An alternative approach to the utilization of lake sapropel is its mixing with available organic sorbents, such as chopped cereal straw. The application of such mixtures in strips into the soil ensures the formation of a moisture-holding nutrient layer during crop cultivation. To form these strips, an experimental prototype of a single-row machine was developed. Under laboratory conditions, the torque M required to drive the machine and the mixture mass flow rate Q were investigated. The variable parameters included the rotational speed of the metering beater shaft n, the blade inclination angle ξ, the width of the hopper outlet opening a, and the opening position of the metering beater housing gate Δ. To obtain mathematical models of the machine drive torque $M(a,\Delta,\xi,n)$ and the mixture mass flow rate $Q(a,\Delta,\xi,n)$ in the form of regression equations, a statistical design of experiments method for a four-factor experiment based on the Box–Behnken design was applied. Analysis of the obtained regression equations showed that, in order to reduce the energy consumption of the machine drive, it is advisable to maintain the beater rotational speed within the range of $n = 550$–600 rpm, the blade inclination angle at $\zeta = 45-50^0$, and the maximum opening of the metering beater housing gate $\Delta = 0.06$ m. A nomogram was developed for regulating the mixture feeding rate of the machine by changing the width of the hopper gate opening a. It was also established that, at the maximum mass flow rate of $Q = 3.5$ kg/s, the torque required for the machine drive M ranged from 6.9 to 7.2 N·m.

РЕЗЮМЕ
Альтернативним способом використання озерного сапропелю є його змішування із доступними органічними сорбентами, наприклад, січкою соломи злакових культур. Внесення таких сумішей смугами у ґрунт забезпечує формування вологоутримуючого поживного шару під час вирощування сільськогосподарських культур. Для формування таких смуг розроблено експериментальний зразок однорядної машини. В умовах лабораторії досліджували крутний момент M, необхідний на привід машини та продуктивність подачі суміші Q. Змінними параметрами були частота обертання вала дозуючого бітера n, кут нахилу лопаті ξ, ширина вихідного отвору бункера a машини та положення заслінки дозуючого бітера Δ. Для отримання математичних моделей крутного моменту приводу машини $M(a,\Delta,\xi,n)$ та продуктивності подачі суміші $Q(a,\Delta,\xi,n)$ у вигляді рівняння регресії було використано математичний метод планування для чотирифакторного експерименту, який базувався на плані Бокса-Бенкіна. Аналізуючи отримані рівняння регресії встановили, що для зменшення енергетичних затрат на привід машини доцільно забезпечувати частоту обертання бітера у межах $n = 550$-600 об/хв., кут нахилу лопаті - $\zeta = 45-50^0$ та максимальну величину відкривання заслінки корпусу дозуючого бітера $\Delta = 0.06$ м. Отримано номограму для регулювання продуктивності подачі суміші машиною шляхом зміни ширини відкривання заслінки бункера a. Також встановлено, що під час досягнення максимальної продуктивності у $Q = 3.5$ кг/с значення крутного момент на привід машини M знаходиться у межах 6.9 до 7.2 Н·м.

INTRODUCTION

A distinctive feature of lake sapropels is their complex influence on all factors determining soil fertility. In particular, numerous studies have reported a positive effect of sapropel and sapropel-based fertilizers on the soil water–air regime and thermal conditions. When sapropel is applied to the soil, an increase in total and capillary water capacity, water-holding capacity, and moisture content of the upper soil horizon is observed (*Baksiene et al., 2015; Edesi et al., 2020; Shevchuk, 1996; Skrylnyk et al., 2021*). It has also been established that the extent of improvement in the water–physical properties of soil depends both on the application rate of sapropel fertilizers and on their quality, particularly their chemical and mechanical composition.

At the same time, the commonly known methods of using sapropel as a fertilizer involve its dewatering from the natural moisture content of deposits, typically ranging from 92–98%, down to approximately 60% *(Booth et al., 2007; Bulgakov et al., 2017; Zarina et al., 2023*). Dewatering sapropel to such a moisture level is associated with significant energy consumption and financial costs, which in turn increases the cost of fertilizers produced on its basis.

It is also well known that achieving high yields of agricultural crops is largely constrained by climate change in general and, in particular, by the catastrophic depletion of soil moisture reserves. Recent studies (*Didukh et al., 2024*) have demonstrated the possibility of forming a nutrient, moisture-holding layer from sapropel and sapropel-based mixtures capable of accumulating water and, when necessary, releasing it to the surrounding soil layers and plants.

Climate change, the energy crisis, and ongoing soil degradation processes are forcing farmers to move away from conventional farming systems and to adopt energy- and resource-saving technologies, such as Mini-till, No-till, Strip-till, and Verti-till (*Jaskulska et al., 2020; Kargwal et al., 2022; Kosolap and Krotinov, 2011*). Among these systems, Strip-till technology has become increasingly widespread. This approach replaces traditional row cultivation with strip cultivation, typically characterized by inter-row spacings ranging from 30 to 75 cm.

These trends create favorable conditions for the local application of fertilizers based on sapropel of natural moisture content for crops grown using wide-row planting systems. This solution is particularly relevant for soils with a light mechanical composition that are located in close proximity to sapropel deposits. Such fertilizers may consist of sapropel mixtures with readily available organic sorbents, for example, chopped cereal straw (*Didukh et al., 2024*).

Existing designs and studies of equipment for the local strip application of organic fertilizers in orchards and for row crops (*Glancey and Adams, 1996; Laguë et al., 2006; Popa et al., 2025; manufacturer data: Renmark*) are generally based on conventional manure spreaders additionally equipped with transverse belt or screw conveyors, or with horizontal spreading discs. These machines enable the placement of organic fertilizer strips on the soil surface near tree trunks, berry bushes, vineyards, or within the inter-rows of row crops. For the local strip application of liquid organic fertilizers into the soil, tank units equipped with cultivators have been developed. Such systems perform soil tillage according to the Strip-till concept and typically form from 4 to 12 fertilizer strips, with inter-row spacings varying from 45 to 75 cm *(manufacturer data: Vogelsang*). For the subsurface strip application of solid organic fertilizers, machines employing flexible screw-type distribution devices have also been developed and tested (*Landry et al., 2011*). However, the aforementioned machines are not suitable for the application of sapropel-based mixtures or for the formation of a moisture-holding nutrient layer due to specific design features that prevent their working elements from handling materials with increased stickiness and viscosity. Taking into account the advantages and limitations of the existing machine designs, a modernized organic fertilizer spreader was developed to enable the formation of subsurface strips of high-moisture solid organic fertilizers for the cultivation of wide-row crops (*Didukh et al., 2024*).

The primary quality parameter of machines designed for uniform surface application of organic fertilizers is the uniformity of distribution. Consequently, numerous experimental and theoretical studies have been devoted to determining the influence of spreading unit parameters on the uniformity of fertilizer distribution over the field surface (*Duhovnik et al., 2004; Cârdei et al., 2019; Ştefan (Popa) et al., 2015; Stefan et al., 2021*).

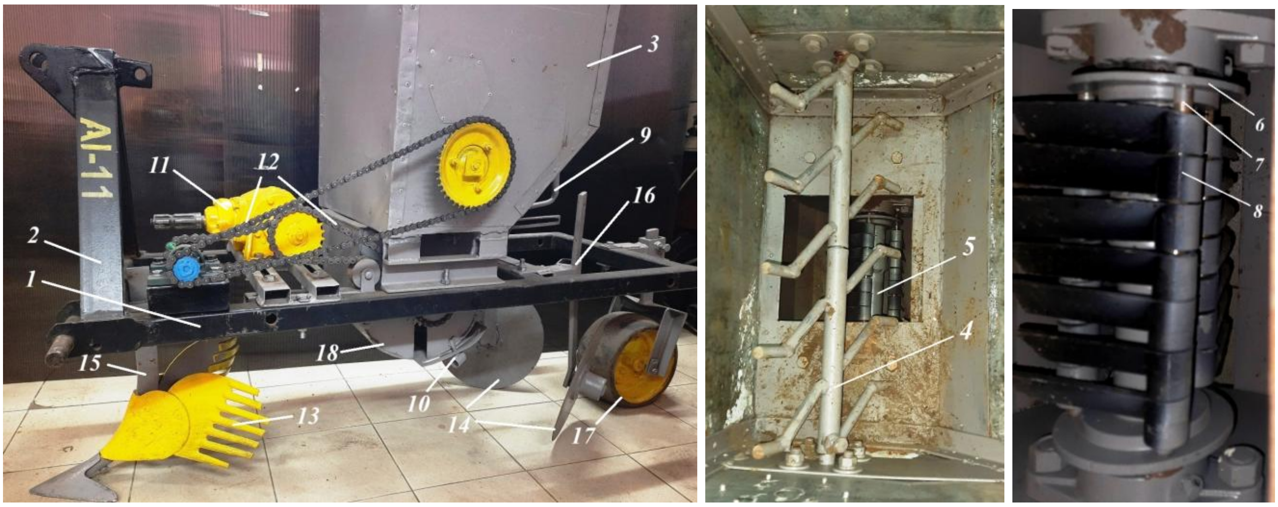
Well-known theoretical and experimental studies of organic fertilizer application machines have also focused on evaluating the influence of hopper geometry and conveying system parameters on machine energy consumption and on the characteristics of the outgoing fertilizer flow (*Landry et al., 2005; Ştefan et al., 2017*).

For machines performing strip application of organic fertilizers, experimental investigations have established specific energy consumption values and deviations in application rates for individual strips (*Laguë et al., 2006; Landry et al., 2011*). In recent years, there has also been a widespread implementation of advanced computer-aided design and simulation tools for the development and modeling of organic fertilizer spreaders and their working elements (*Sengottaian et al., 2019; Stefan et al., 2025*).

The aim of this study is to investigate the influence of the main design and technological parameters of the working elements of a modernized organic fertilizer spreader (*Didukh et al., 2024*) on the drive torque and the mixture mass flow rate of the machine.

MATERIALS AND METHODS

To investigate the developed design of the modernized organic fertilizer spreader (*Didukh et al., 2024*), an experimental prototype of a single-row machine for the local strip application (MLSA) of sapropel-based mixtures was manufactured (Fig. 1a). The machine is based on a frame *1*, on which the hitch mechanism *2* and the fertilizer hopper *3* are mounted. An agitator *4* is installed inside the hopper (Fig. 1b), while a metering beater *5* is located beneath the hopper within its own housing. The metering beater 5 (Fig. 1c) consists of a central shaft fitted with two flanges *6*, each carrying three shafts *7*. Blades 8 are pivotally mounted on the shafts *7*. Regulation of the fertilizer flow supplied from the hopper *3* to the metering beater *5* is performed using a gate *9*, whereas the overall fertilizer application rate is controlled by a gate *10* of the metering beater housing *18*.



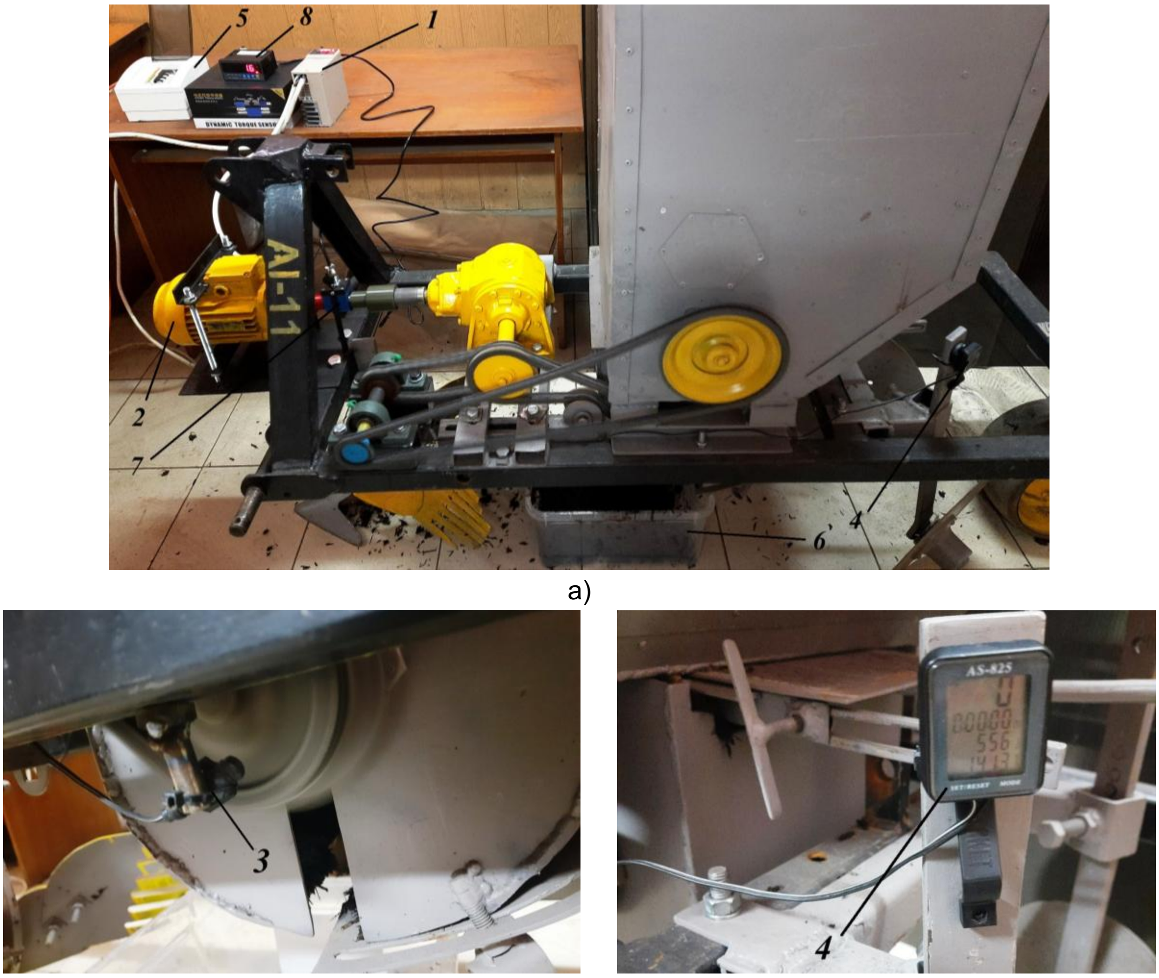
a b c

Fig. 1 - Experimental prototype of the MLSA machine for sapropel and sapropel-based mixtures
(a) *general view;* ***(b)*** *internal part of the hopper;* ***(c)*** *metering beater*

To form the furrow, the machine is equipped with a furrow opener *13*, while furrow covering is performed by disc closers *14*. The furrow depth and the ridge height formed during furrow covering are adjusted by the mechanisms controlling the working depth of the opener *15* and the position of the disc closers *16*, respectively. To ensure a horizontal operating position of the machine, a support wheel *17* is provided, which simultaneously performs the function of soil compaction above the applied fertilizers.

Based on theoretical analysis and literature sources (*Didukh et al., 2024; Laguë et al., 2006*), it was established that the drive torque and the mixture mass flow rate are significantly influenced by the following design and technological parameters: the rotational speed of the metering beater shaft, the angle between the working surface of the blade and the axis of rotation of the metering beater (hereinafter referred to as the blade inclination angle), the width of the machine hopper outlet opening (determined by the position of the hopper gate), and the opening angle of the metering beater housing gate (determined by the position of the metering beater gate).

To investigate the influence of these factors on the torque required to drive the machine M and on the mixture mass flow rate Q, laboratory tests were conducted. For this purpose, the experimental machine prototype was additionally equipped with an asynchronous motor *2*, an electronic rotational speed controller *1*, and a torque sensor *7* with a monitoring unit *8* (Fig. 2). To obtain mathematical models describing the variation of the machine drive torque M and the mixture mass flow rate Q in the form of regression equations, a design of experiments approach for a four-factor experiment based on a second-order, symmetric, non-composite Box–Behnken design, originally proposed by *Box and Behnken, (1960)*, was applied. The factors investigated in the experiment are presented in Table 1. The ranges of variation in the rotational speed of the metering beater shaft and the blade inclination angle were selected based on the results reported by *Didukh et al., (2024)*.



a)

b) c)

Fig. 2 - MLSA machine equipment used for laboratory investigations of sapropel and sapropel-based mixtures:
(a) general view; (b) installation of the Hall-effect sensor; (c) rotational speed monitor.

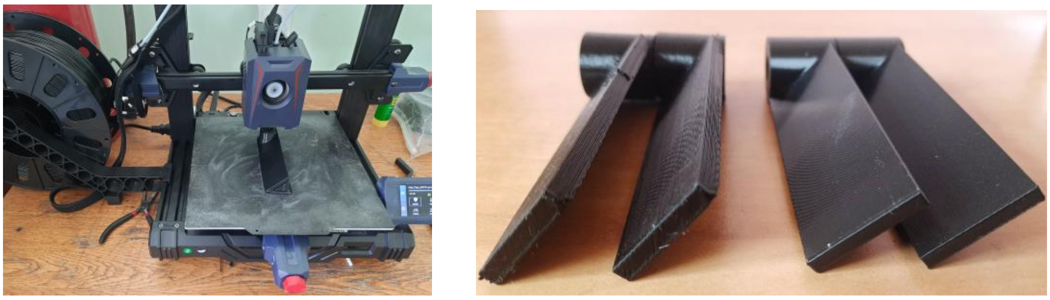
Table 1

Investigated factors and their variation ranges

Variation level	Factors			
	Width of the hopper outlet opening, *a*	Opening of the metering beater housing gate, *Δ* (m)	Blade inclination angle, ζ	Rotational speed of the metering beater shaft, *n*
	[m]	[m]	[deg.]	[rpm]
	x_1	x_2	x_3	x_4
Upper (+1)	0.14	0.08	50	850
Central (0)	0.10	0.06	45	700
Lower (-1)	0.06	0.04	40	550

The investigated factors were fixed at the specified levels as follows. To vary the rotational speed of the metering beater shaft n, a frequency inverter Veichi AC01-T3-1R5G-B (1) was used to control the rotational speed of the asynchronous drive motor (2) (Fig. 2).

The achieved rotational speed of the metering beater shaft was monitored using a Hall-effect sensor (3) and recorded based on the readings of the monitor (4). To vary the blade inclination angle ζ, three sets of blades were manufactured from PLA plastic using 3D printing, with each set consisting of 21 blades (Fig. 3) and corresponding to the angle values listed in Table 1. The suitability of using plastic for blade manufacturing was substantiated in *Tsiz et al., (2026)*. The blade length from the mounting axis was 100 mm, while the width and thickness of the working part were 30 mm and 5 mm, respectively.



a) b)

Fig. 3 – Photograph of the blade manufacturing process with an inclination angle of $\zeta = 45^0$ by 3D printing (a) and the manufactured blades with inclination angles of $\zeta = 40^0$ and $\zeta = 50^0$ (b).

The experiments were carried out using a mixture consisting of 87% sapropel with a moisture content of $W = 92.2$ %, and 11% chopped winter wheat straw with a moisture content of $W = 13.6$ % and a cutting length of 5–20 mm. The moisture content of the mixture was $W = 81.7$ %. The stickiness characteristics of this and other sapropel-based mixtures are presented in *Tsiz et al., (2026).*

After setting the factor values specified by the experimental design in the form of parameters of the experimental setup, the hopper was filled with the above-described mixture, and the power supply of the frequency inverter Veichi AC01-T3-1R5G-B (1) was switched on using the control panel (5). Subsequently, the electric current frequency corresponding to the rotational speed of the beater shaft required by the experimental plan was set on the inverter display, and the power supply of the electric motor (2) was switched on. During the experiment, the mixture delivered by the metering beater was collected in a container (6) (Fig. 2). Each experimental run involved operating the machine for 20 s, after which the drive was switched off. During the experiment, between the 15th and 20th second of machine operation, the torque value measured by the sensor (7) was recorded based on the readings of the monitor (8).

The mixture mass flow rate of the machine, expressed in kg/s, was determined by dividing the mass of the mixture collected in the container (6) (Fig. 2) during one experimental run by the duration of the experiment (20 s). All experiments aimed at determining the drive torque and the mixture mass flow rate at the factor levels specified by the experimental design were performed in three replicates.

RESULTS

To process the experimental data obtained for the drive torque and the mixture mass flow rate, the methodology described in *Box and Behnken, (1960)* and *Tsiz and Homich, (2013)* for a four-factor experimental design was applied. The calculations were performed using Mathcad software. The reproducibility of the experiment was confirmed using Cochran's test. For the drive torque, the calculated value of the Cochran criterion satisfied the condition $G^{calc} = 0.110 < G^{tab}(0.05;27;2) = 0.318$ and for the mixture mass flow rate of the machine, the corresponding condition – $G^{calc} = 0.213 < G^{tab}(0.05;27;2) = 0.318$ was also fulfilled. The maximum standard deviation of the experimental torque values was $S = 0.49$ N·m, whereas the corresponding value for the mixture mass flow rate was $S = 0.22$ kg/s.

The significance of the regression coefficients was evaluated using confidence intervals determined according to Student's *t*-test. The tabulated value of this criterion at a 5% significance level and with the corresponding number of degrees of freedom of the reproducibility variance $f_1 = 2$ was $t = 4.3$.

After excluding the terms with statistically insignificant coefficients, the regression equations took the following form:

– for the drive torque

$$y_1 = 4.7 + 1.467 \cdot x_1 - 0.233 \cdot x_2 - 0.133 \cdot x_3 + 1.017 \cdot x_4 + \\ +0.275 \cdot x_1 \cdot x_4 + 0.188 \cdot x_1^2 - 0.388 \cdot x_2^2 + 0.187 \cdot x_4^2 \quad (1)$$

– for the mixture mass flow rate

$$y_2 = 1.29 + 1.007 \cdot x_1 + 0.101 \cdot x_2 + 0.455 \cdot x_4 + 0.156 \cdot x_1 \cdot x_4 + 0.436 \cdot x_1^2 + 0.262 \cdot x_4^2 \quad (2)$$

where: x_1, x_2, x_3, x_4 - are the coded values corresponding to the following factors: the width of the hopper outlet opening a, the opening of the metering beater housing gate Δ, e blade inclination angle ζ, and the rotational speed of the metering beater shaft n, respectively.

The adequacy of the regression equations was verified using Fisher's test. The calculated value of this criterion for the drive torque, with the variance of inadequacy $S_{n.}^2 = 0.00502$ and the variance of experimental reproducibility $S_y^2 = 0.01$ was $F^{calc} = 5.02$. The tabulated value of Fisher's criterion at the adopted 5% significance level was:

$$F^{tab}(0.05; f_2; f_1) = 19.43 \quad (3)$$

where: $f_2 = 18$ - is the number of degrees of freedom of the inadequacy variance;

$f_1 = 2$ - is the number of degrees of freedom of the experimental reproducibility variance.

Since

$$F^{calc.} = 5.02 < F^{tab}(0.05; f_2; f_1) = 19.43 \quad (4)$$

the hypothesis of adequacy of the regression equation, for which the response function is the drive torque required for machine operation, is confirmed.

The calculated value of Fisher's criterion for the mixture mass flow rate, with the inadequacy variance $S_{n.}^2 = 0.011$ and the experimental reproducibility variance $S_y^2 = 3.612 \times 10^{-3}$ was equal to $F^{calc} = 3.011$. The tabulated value of Fisher's criterion at the adopted 5% significance level was:

$$F^{tab}(0.05; f_2; f_1) = 19.44 \quad (5)$$

where: $f_2 = 20$ - is the number of degrees of freedom of the inadequacy variance;

$f_1 = 2$ - is the number of degrees of freedom of the experimental reproducibility variance.

Since

$$F^{calc.} = 3.011 < F^{tab}(0.05; f_2; f_1) = 19.44 \quad (6)$$

the hypothesis of adequacy of the regression equation, for which the response function is the mixture mass flow rate, is confirmed.

After converting the factors to their natural values, the regression equations (7) for the drive torque and (8) for the mixture mass flow rate of the machine were obtained. The reported precision of the regression coefficients was required to ensure the adequacy of the developed regression equations. Based on equation (7), response surfaces were constructed (Fig. 3a–c), whereas two-dimensional cross-sections of the response surface were generated based on equation (8) (Fig. 3d).

$$M = 3.14627778 - 18.90833333 \cdot a + 104.75 \cdot \Delta - 0.0266 \cdot \xi - 0.00943889 \cdot n + \\ +0.04583333 \cdot a \cdot n + 117.5 \cdot a^2 - 970.0 \cdot \Delta^2 + 8.31 \cdot 10^{-6} \cdot n^2 ; \quad (7)$$

$$Q = 6.59694444 - 47.525 \cdot a + 5.05 \cdot \Delta + 0.01586889 \cdot n + \\ +0.026 \cdot a \cdot n + 272.5 \cdot a^2 + 1.164 \cdot 10^{-5} \cdot n^2 , \quad (8)$$

where: M - the drive torque required for machine operation [N·m];

Q - the mixture mass flow rate of the machine [kg/s].

The analysis of the regression equation for the drive torque required for machine operation (1) and the corresponding response surfaces (Fig. 4a–c) indicates a significant influence of all the investigated factors on this parameter. An increase in the drive torque is caused by an increase in the hopper outlet width a and the rotational speed of the metering beater shaft n. For factor a, this effect is associated with an increase in the mass of the mixture supplied by the metering beater per unit time, whereas for factor n, it is explained by the increased aerodynamic resistance acting on the rotating rotor blades.

In turn, an increase in the blade inclination angle ζ leads to a reduction in the projected area of the blade surface onto the plane perpendicular to the direction of rotation, which results in a decrease in aerodynamic resistance. The reduction in the drive torque with increasing opening of the metering beater housing gate Δ is evidently caused by a decrease in resistance during the discharge of the mixture from the rotor blades through the outlet opening of the housing.

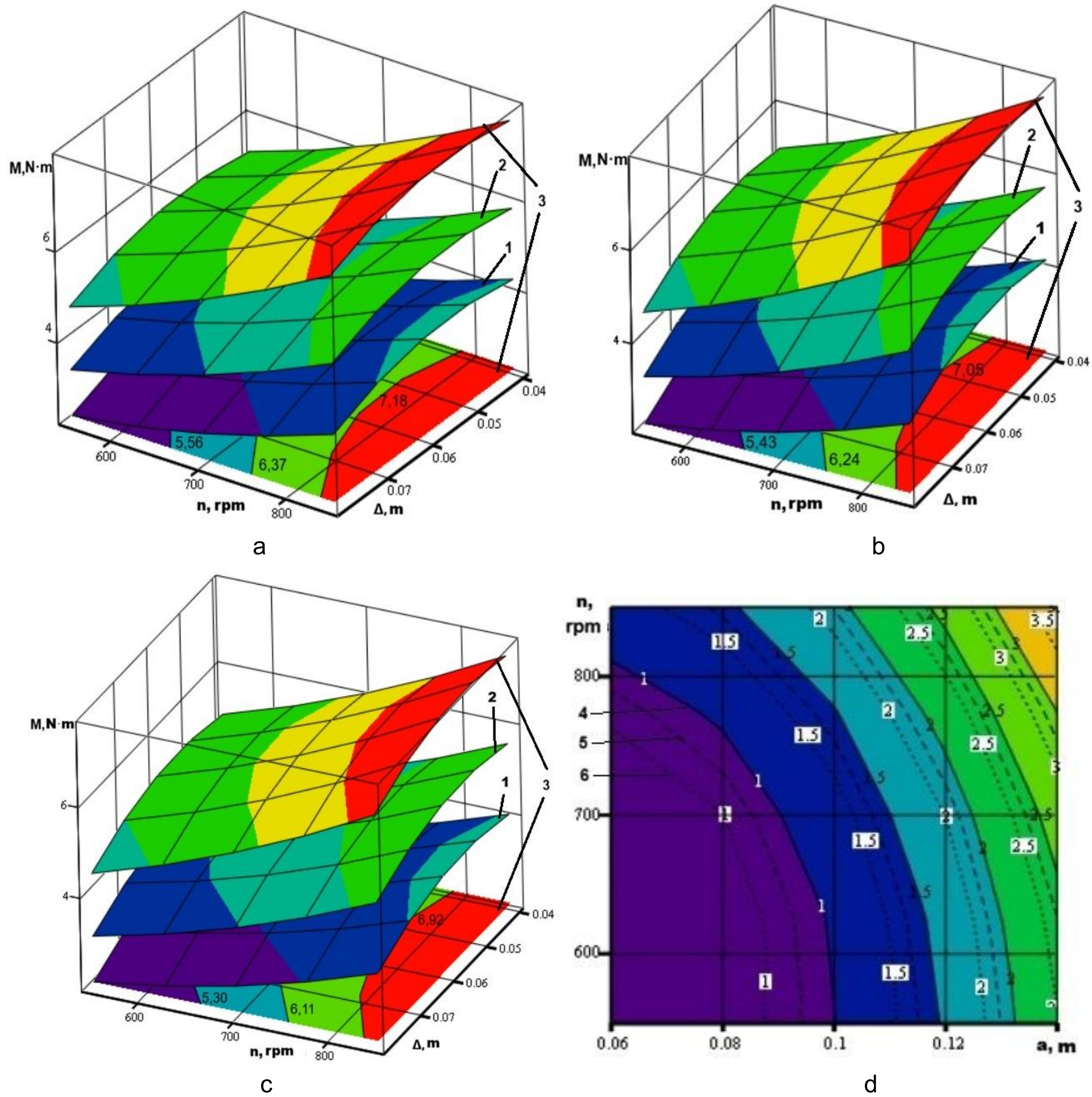


Fig 4 – Response surfaces constructed using equation (7) (a–c) and contour plots generated based on equation (8) (d).

a - $\zeta = 40^0$; b - $\zeta = 45^0$, c - $\zeta = 50^0$; 1 - $a = 0.06$ m; 2 - $a = 0.10$ m; 3 - $a = 0.14$ m; 4 - $\Delta = 0.04$ m; 5 - $\Delta = 0.06$ m; 6 - $\Delta = 0.08$ m

At the same time, the analysis of Equation (2) and the corresponding plots (Fig. 4d) indicates that the blade inclination angle ζ has no significant effect on the mixture mass flow rate. An increase in the mixture mass flow rate is observed with increasing rotor rotational speed n and hopper outlet width a.

Based on a comparison of the plots for the drive torque M (Fig 4, a-c) and the mixture mass flow rate Q (Fig 4, d) it was established that an increase in productivity Q is accompanied by an increase in the drive torque required for machine operation M. In order to achieve the maximum productivity $Q = 3.5$ kg/s the maximum drive torque values M in the range of 6.9–7.2 N·m are required.

Visual observations of the MLSA operation demonstrated stable performance without adhesion of the moist mixture to the working surfaces of the beater blades over the entire investigated range of factor variation (Table 1).

Therefore, in order to reduce energy consumption for machine operation, it is advisable to maintain the beater rotational speed within the range of $n = 550–600$ rpm, a blade inclination angle of $\zeta = 45 - 50^0$, and the maximum opening of the metering beater housing gate $\Delta = 0.06$ m.

Under these conditions, the required fertilizer application rate should be adjusted by selecting the hopper outlet width a using the plot shown in Fig. 4d as a regulating nomogram.

To compare the experimentally obtained values of drive torque M and productivity Q with the results obtained in studies of similar machines mentioned above, it is necessary to test the MLSA under field conditions. Laboratory investigations confirmed the operability of the developed design and the correctness of the adopted design solutions, which ensure self-cleaning of the blades when working with mixtures of increased stickiness.

A further development of the conducted research is the design of a multi-row machine capable of forming strips of a moisture-holding nutrient fertilizer layer during the cultivation of crops with different inter-row spacings. The design of such a machine can be developed by modernizing existing organic fertilizer spreaders using the proposals described in *Didukh et al., (2024)*.

CONCLUSIONS

Based on previous studies and existing designs of machines for organic fertilizer application, an experimental prototype of a single-row MLSA was developed. Equipping the MLSA with an electric drive, a frequency controller, and a torque sensor enabled experimental investigations of its operation under laboratory conditions.

The conducted MLSA studies, using a mathematical design of experiments approach, made it possible to obtain regression-based mathematical models describing the dependence of the drive torque $M(a,\Delta,\xi,n)$ and the mixture mass flow rate $Q(a,\Delta,n)$ on the investigated factors.

It was established that achieving the maximum productivity $Q = 3.5$ kg/s requires the maximum drive torque M values in the range from 6.9 to 7.2 N·m. In order to reduce energy consumption during machine operation, it is advisable to maintain the beater rotational speed within the range of $n = 550\text{-}600$ rpm, the blade inclination angle $\zeta = 45 - 50^0$ and the maximum opening of the metering beater housing gate $\Delta = 0.06$ m. Under these operating conditions, the required fertilizer application rate should be set by selecting the hopper outlet width a, using the plot shown in Fig. 4d as a regulating nomogram.

Future research will focus on field testing of the MLSA and on the development of a multi-row machine capable of forming strips of a moisture-retaining nutrient fertilizer layer for crops grown with different row spacings.

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