ANALYSIS OF ROOT CROP SCREW GRINDER-MIXER PERFORMANCE

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Abstract. Screw conveyors are widely used as conveying mechanisms in the agricultural sector, as well as in the processing and food industries, where their application is determined by a wide range of technological processes related to harvesting and processing crop products. Improvement of the design of screw conveying mechanisms and substantiation of their rational parameters and operating modes are important tasks aimed at increasing the productivity and reliability of technological operations. The purpose of this study is to develop analytical-empirical models describing the variation in the productivity of a screw root crop grinder–mixer depending on its structural and kinematic parameters. The study presents the results of analytical and experimental investigations of a screw grinder–mixer for root crops designed as a horizontal casing with a combined screw conveyor placed inside it. The screw conveyor is made in the form of a rotating drum with screw blades on which cutting knives are installed, which ensures simultaneous transportation, crushing and mixing of root vegetables during operation. Based on the experimental results, a regression equation describing the functional dependence of the productivity of the improved screw grinder–mixer on the investigated parameters was obtained. It was established that within the investigated ranges of the input factors (screw rotational speed from 100 to 300 rpm, screw outer diameter from 0.12 to 0.20 m, and helical flight pitch from 0.05 to 0.11 m), the throughput capacity of the screw grinder-mixer for root crops varies within the range from 0.14 to 1.7 $kg \cdot s^{-1}$. The results obtained contribute to the further development of the methodological base for substantiating the rational parameters of screw transport mechanisms and can be used in the improvement of machines intended for processing root crops.

Keywords: model, process, screw conveyor, knife, experiment, parameters.

Introduction

Screw conveyors are among the most widely used mechanical conveying devices for handling bulk and semi-bulk materials in agriculture, food industry, and various processing sectors. Their popularity is explained by a relatively simple design, operational reliability, compact dimensions, and the ability to perform several technological operations simultaneously, including transportation, mixing, and processing of materials. In agricultural production, screw conveyors are commonly used for transporting and processing grain, feed mixtures, root crops, and other agricultural raw materials. In livestock production, root crops represent an important component of feed rations due to their high nutritional value and availability. However, before being fed to animals, root crops require mechanical processing such as crushing, grinding, and mixing. These technological operations are necessary to improve feed digestibility and ensure uniform distribution of feed components within the mixture. According to previous studies, the efficiency of feed preparation processes significantly depends on the design parameters and operating modes of the processing equipment [1; 2].

Screw-type machines are widely applied in feed preparation systems because they allow the integration of several technological operations within a single working unit (Fig. 1). In particular, screw conveyors equipped with cutting elements can simultaneously transport, grind, and mix feed components. Such multifunctional devices improve technological efficiency and reduce energy consumption and labour costs in feed preparation processes [3; 4].

A considerable number of studies have been devoted to the investigation of screw conveying mechanisms and the determination of their rational design parameters. Previous research has focused on the theoretical analysis of the movement of bulk materials in screw channels, the influence of screw geometry on conveying efficiency, and the optimization of screw conveyor performance [5-7]. Nevertheless, the productivity of screw mechanisms strongly depends on several structural and kinematic parameters, including the rotational speed of the screw, the screw diameter, and the pitch of the helical flights. The combined influence of these parameters on the productivity of multifunctional screw machines used for processing root crops remains insufficiently investigated.

Therefore, further experimental and analytical studies aimed at determining the rational parameters of screw conveying mechanisms are necessary. The development of mathematical models describing the functional relationships between machine productivity and its operating parameters can significantly improve the design and performance of such equipment.

The aim of this research is to develop analytical-empirical models describing the productivity of a screw root crop grinder-mixer depending on its main structural and kinematic parameters.

Materials and methods

Based on the analysis of the existing generalized structural scheme of root crop processing operations for feed preparation, a scientific hypothesis was proposed, which assumes the technical and technological possibility of combining three separate but related operations - root crop grinding, transportation of crushed root crops and mixing into a single integrated technological operation, which is implemented by one technical device, namely a screw root crop grinder-mixer. This approach allows to significantly reduce energy consumption during the preparation of the feed mixture.

In order to determine the functional dependence of the productivity of the screw root crop grinder-mixer on the variation of input parameters, a laboratory experimental installation was developed (Fig. 1).

The main components of the experimental setup include the screw grinder–mixer 8, the control device Altivar 71 frequency converter 14, and a personal computer 15 used for monitoring and controlling the experimental process.

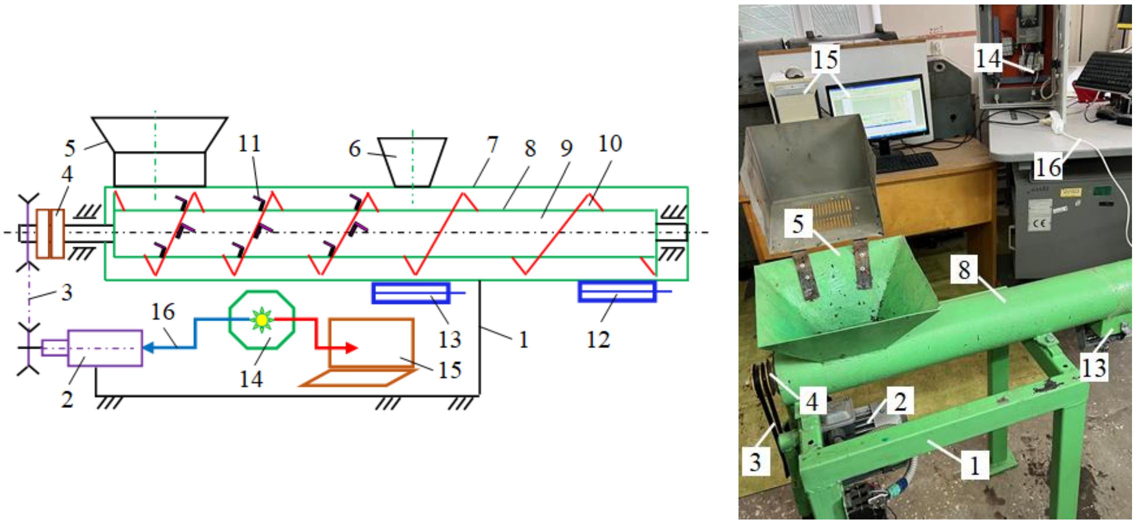

Fig. 1. **Structural diagram (a) and general view (b) of the laboratory installation:** 1 – frame; 2 – electric motor; 3 – V-belt drive; 4 – coupling; 5, 6 – hopper; 7 – casing; 8 – combined screw conveyor; 9 – drum; 10 – spiral; 11 – knife; 12, 13 – gate valve, 14 – Altivar 71 control device; 15 – computer; 16 – means of communication

The main structural elements of the screw root crop grinder–mixer are the supporting frame 1 (Fig. 1), on which the electric motor 2, horizontal casing 7, hopper for root crops 5, hopper for feed additives 6, and the combined screw conveyor 8 are mounted. The primary working element of the machine is the combined screw conveyor 7, which performs several technological operations simultaneously: transportation of processed materials (root crops and feed additives), crushing of root crops, and mixing of crushed root crop particles with feed additives. The combined screw conveyor consists of a rotating drum 9 equipped with helical flights 10 arranged along the screw line. Cutting knives 11 are mounted on the surface of the helical flights and are responsible for the crushing of root crops during operation.

The mixing of crushed root crop particles with feed additives occurs in the section of the screw conveyor designed as a conventional screw mechanism with a variable pitch of the helical flights, which intensifies the mixing process. The resulting feed mixture is transported by the screw flights towards the discharge gate 13, where it is unloaded for further use.

Such a structural configuration makes it possible to combine several technological processes within a single working unit, which increases the efficiency of feed preparation and reduces energy consumption.

The following factors were selected as independent variables within the specified ranges of variation: the rotational speed of the screw conveyor $100 \le n_k \le 300$ rpm; the outer diameter of the screw conveyor $0.12 \le D_k \le 0.2$ m; the pitch of the helical flights $0.05 \le T_s \le 0.11$ m.

To implement the planned factorial experiments of the PFE 3^3 type, an asymmetric Box–Benkin design matrix was constructed [8]. The sequence of each experiment was carried out in accordance with the numbered order of the randomized design matrix, and randomization was carried out using the random balance method.

The order of the experiments was as follows. Before starting the experiments, the following preparatory operations were performed.

1. The Power Suite version 2.3.0 software, designed to control the Altivar 71 multi-system device, was downloaded to the root directory of the computer 15 (Fig. 1).
2. The rotation frequency n_k of the combined screw conveyor 8 (Fig. 1) was set by adjusting the rotation frequency of the electric motor shaft 2 taking into account the gear ratio of the V-belt transmission 3.
3. The numerical value of the motor rotor speed was set by a command from the virtual oscilloscope control panel, which was displayed on the computer monitor 15 (Fig. 1). The actual value of the motor shaft speed 2, which was displayed in the virtual oscilloscope window, was determined using a sensor of the E40S6-10Z4-6L-5 type, connected simultaneously to the motor rotor and the Altivar 71 device.
4. The root crops were loaded into the hopper 5 (Fig. 1) of the screw conveyor of the grinder-mixer 8, the time of the experiment was set using the electronic timer of the Altivar 71 device, and the electric motor 2 was started by a command from the control panel.
5. After the end of the experiment, or the automatic stop of the electric motor 2 (Fig. 1) due to a command from the Altivar 71 device operation control system, the crushed root crops were weighed on the PS.200/2000.R1 electronic scales with an accuracy of ±0.01 kg.

The productivity was calculated according to the following expression

$$Q_{ke} = U_k\left(t_e\right) / t_e, \tag{1}$$

where Q_{ke} – productivity of the screw grinder-mixer, kg·s^{-1};
$U_k(t_e)$ – mass of processed root crops, kg;
$t_e = 10$ s – processing time.

The obtained experimental data were averaged over three repetitions to reduce random measurement errors.

Results and discussion

Based on the results of theoretical analysis of the root crop grinding process, a mathematical model was obtained that functionally describes the change in the productivity Q_k of the screw conveyor-grinder for root crops

$$Q_k = \frac{\pi n_k D_k^2 \rho_k \psi_\alpha T_s k_a k_y}{240}\left(1 - k_n\right), \tag{2}$$

where Q_k – productivity of the screw grinder-mixer, kg·s^{-1};
n_k – rotational speed of the screw conveyor, rpm;
D_k – diameter of the screw conveyor, m;
ρ_k – specific gravity of root vegetables, kg m^{-3};
T_s – spiral pitch, m;
k_a, k_y – respectively, the coefficient showing the degree of influence of the helix elevation angle of the last turn of the screw conveyor and the compaction coefficient of the crushed root crops and coefficient of filling the space of the screw conveyor;
k_n – coefficient of filling the space of the screw conveyor.

The theoretical value of the productivity Q_k of the screw crusher-mixer varies from 0.5 to 1.9 kg·s^{1} (Fig. 2) depending on the change in the main parameters of the screw conveyor, while the change in Q_k

has a directly proportional functional character – with an increase in the rotation frequency n_k, diameter D_k, pitch T_s of the spiral turns of the screw conveyor, the productivity increases.

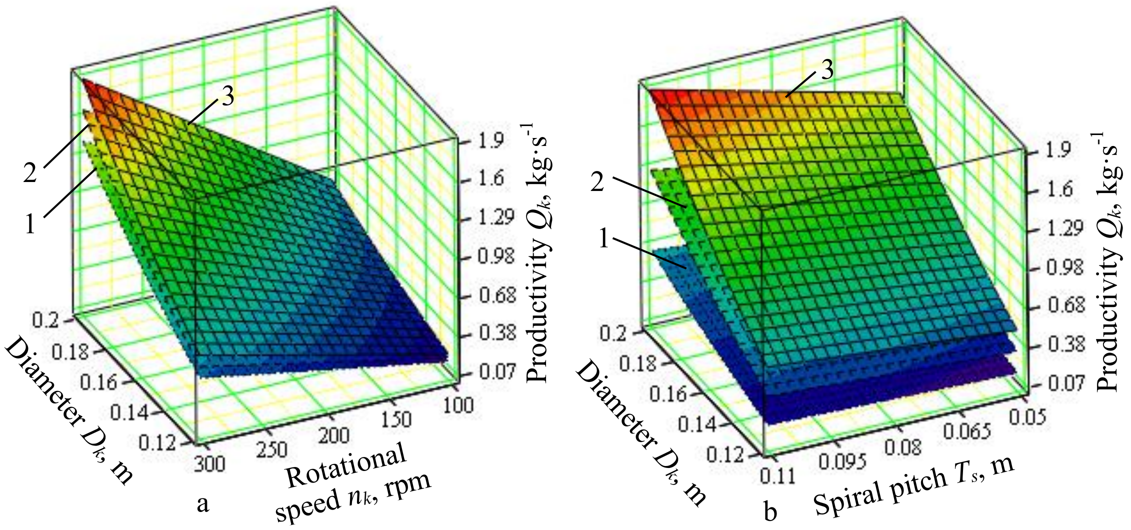

Fig. 2. **Dependence of the change in theoretical productivity of a screw crusher-mixer as a function of:** a – $Q_k = f(n_k;D_k)$; b – $Q_k = f(D_k;T_s)$

A significant increase in the theoretical productivity Q_k of the screw crusher-mixer occurs at a diameter value of D_k = 0.16 m and a screw conveyor rotation frequency of n_k = 200 rpm. To verify the adequacy of the mathematical model (2), experimental studies were conducted to determine the productivity of the screw grinder-mixer of root crops depending on the speed of rotation of the screw conveyor, its diameter and the pitch of the spiral turns.

To determine the influence of the investigated factors on machine productivity, regression analysis was applied. A second-order polynomial regression model was used to describe the functional relationship between productivity and the investigated parameters.

Based on the results of multivariate regression analysis, the second-order equation was obtained

$$Q_{ke} = 1.24 - 0.004n_k - 15.32D_k - 4.08T_s + 1.15\cdot 10^{-6} n_k^2 + \\ +40.51D_k^2 - 5.14T_s^2 + 0.04n_kD_k + 0.01n_kT_s + 42.36D_kT_s \quad . \tag{3}$$

The obtained regression equation makes it possible to estimate the productivity of the screw conveyor within the investigated parameter ranges.

The coefficient of determination of the obtained model is R^2 = 0.989, which indicates a high degree of agreement between the calculated and experimental results. This confirms that the regression equation adequately describes the investigated process [9]. The adequacy of the regression model was verified using the Fisher criterion [10]. The calculated value of the Fisher criterion is F_c = 168.92, which significantly exceeds the tabulated value F_{tab}(0.05;9;17) = 2.49 at the 0.05 significance level. Therefore, the obtained regression model can be considered statistically adequate – F_c = 168.92 >> F_{tab} = 2.49. The significance of the regression coefficients was evaluated using the Student's t-test [11]. The analysis showed that the most influential factors affecting the productivity of the screw conveyor are the screw rotational speed and its diameter. In addition, the interaction between these parameters also has a significant effect on the performance of the conveyor. The influence of the screw pitch is less pronounced but still contributes to improving the conveyor productivity.

Based on the analysis of the graphical interpretation of the experimental results, or the constructed response surfaces (Fig. 3), it was found that: the productivity values obtained during the experiments varied within the range from 0.14 to 1.70 kg·s^{-1}; the lowest productivity was observed at the minimum values of the investigated parameters (n_k = 100 rpm, D_k = 0.12 m, T_s = 0.05 m), whereas the highest productivity corresponded to the maximum parameter levels (n_k = 300 rpm, D_k = 0.20 m, T_s = 0.11 m). An increase in the rotational speed from 100 to 300 rpm leads to a substantial increase in productivity due to the higher rate of material movement along the screw channel. At the same time, increasing the screw diameter increases the volume of the material transported between the screw flights, which also contributes to higher productivity. The pitch of the helical flights has a comparatively smaller effect on productivity.

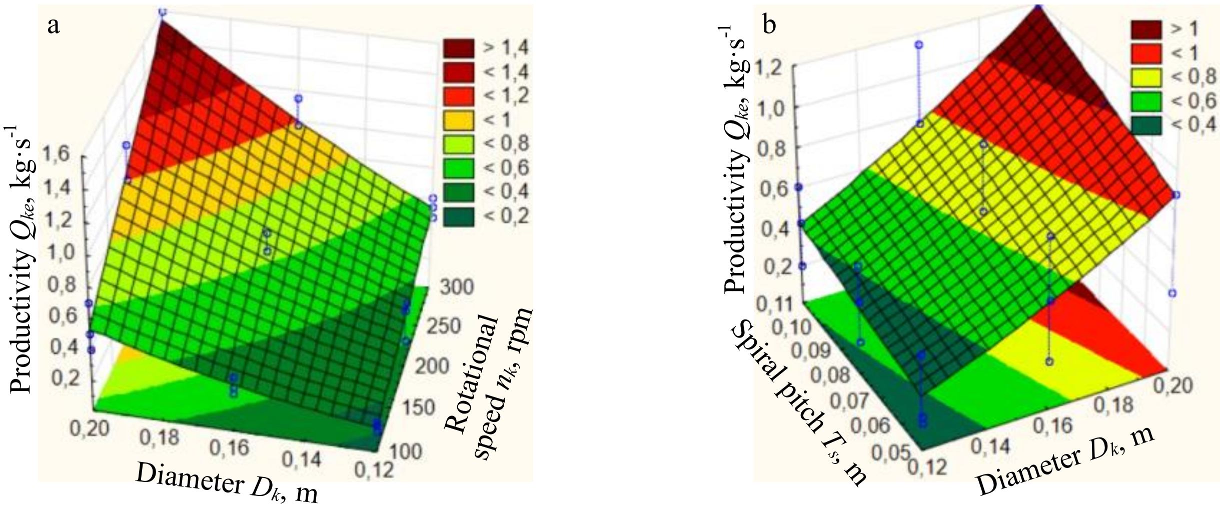

Fig. 3. **Response surface of the performance change as a function of:**
a – $Q_{ke} = f(n_k;D_k)$; b – $Q_{ke} = f(D_k;T_s)$

However, an increase in the pitch slightly increases the productivity because it enlarges the working space between the screw flights and improves the movement of the material.

Optimization of the regression model within the investigated parameter range showed that the maximum productivity of the screw conveyor is achieved at a rotational speed of 300 rpm, a screw diameter of 0.20 m, and a screw pitch of 0.11 m. Under these conditions, the predicted productivity reaches approximately 1.72 kg·s^{-1}.

The discrepancy between the theoretical and experimental values of the productivity of the screw crusher-mixer, which are obtained by formulas (2) and (3), is in the range from 10 to 15%, Fig. 4.

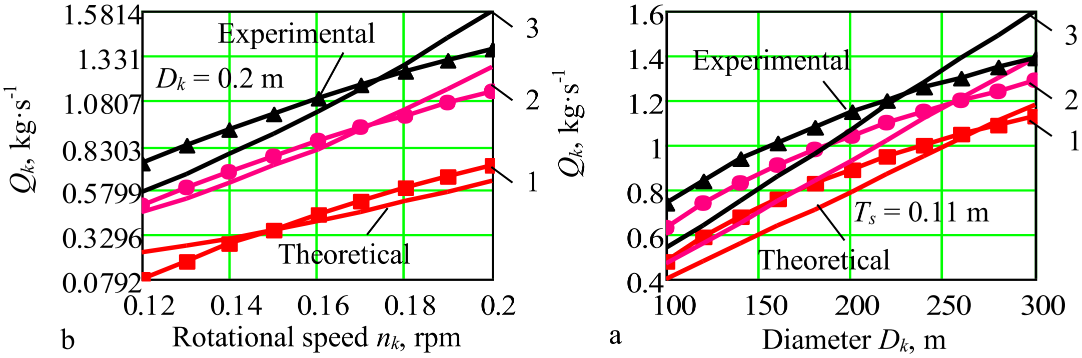

Fig. 4. **Dependence of the change in productivity as a function of:** a – $Q_k = f(n_k;)$,
1, 2, 3 – respectively, T_s = 0.05; 0.08; 0.11 m; b – $Q_k = f(D_k;)$,
1, 2, 3 – respectively, n_k = 100; 200; 300 rpm

Thus, it can be stated that the developed theoretical model (2) is adequate to the empirical model (3) and satisfactorily describes the functional change in the experimental values of the productivity of the screw conveyor of the grinder-mixer, which were obtained in the process of conducting experimental research.

Conclusions

The conducted experimental study made it possible to determine the influence of the main design and kinematic parameters of the screw conveyor on its productivity and to develop an adequate mathematical model describing the investigated process. Based on the results of multifactor experimental studies, a second-order regression equation was obtained that describes the dependence of the screw conveyor productivity on the screw rotational speed, screw diameter and helical flight pitch.

The experimental results showed that increasing the screw rotational speed from 100 to 300 rpm leads to a substantial increase in productivity due to the intensification of the material transportation process along the screw channel. Increasing the screw diameter from 0.12 to 0.20 m also significantly increases productivity by enlarging the effective volume of the material transported between the screw flights. Optimization of the obtained regression model within the investigated parameter ranges allowed determination of the rational operating parameters of the screw conveyor. The maximum productivity of approximately 1.72 $kg \cdot s^{-1}$ is achieved at a screw rotational speed of 300 rpm, screw diameter 0.20 m, and screw pitch 0.11 m.

The obtained results can be used in the design and optimization of screw conveying equipment for agricultural materials, as well as for improving the efficiency of technological processes involving bulk material transportation. Thus, the developed mathematical model and the established rational parameters provide a scientific basis for improving the design and operational efficiency of screw conveyors used in agricultural production systems.

The obtained results confirm the possibility of improving the efficiency of screw conveyors by selecting rational structural and kinematic parameters. The developed regression model can be used for engineering calculations and optimization of screw conveyor design parameters.

Author contributions

Conceptualization, Viktor Baranovsky and Vitalii Pankiv; methodology, Viktor Makarov and Roman Komar; software, Viktor Baranovsky and Viktor Tesliuk; formal analysis, Vitalii Pankiv and Viktor Makarov; investigation, Viktor Baranovsky and Viktor Tesliuk; structural diagram of the conveyor of the root crop chopper-displacer, Viktor Makarov; writing – original draft preparation, Vitalii Pankiv and Roman Komar; writing – review and editing, Viktor Baranovsky and Roman Komar. All authors have read and agreed to the published version of the manuscript.

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