UDK 631.313
IRSTI 68.01.11
DOI 10.52578/2305-9397-2025-3-4-135-143

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DEVELOPMENT OF A LABORATORY SOIL BIN FOR SOIL-ACTIVELY DRIVEN ROTARY TILLAGE TOOL INTERACTION STUDIES

ANNOTATION

Tillage machines with power-driven rotary tillage tools are promising in agriculture. These tools have become the subject of scientific research and industrial applications in modern agriculture. However, their further improvement is limited by the poorly understood process of their interaction with the soil. The aim of the study is to increase the efficiency of tillage process through the research, development and application of actively driven rotary tillage tools. For the study, three types of actively driven rotary tillage tools were selected: a cylindrical ring tillage tool, a knife tillage tool and a rotary tillage tool with covering elements. The article presents the results of work on the development of a laboratory soil bin for conducting experimental studies of the interaction of soil – tillage tools. During the study, the angle of inclination from travel direction can be adjusted stepwise to 40°, 70° and 90°. The inclination angle from vertical plane can vary between -30° (backward), 0° (vertical), +20° and +40° (forward). The coefficient of kinematic mode was studied in the range of $0.6 \leq \lambda \leq 1.4$. The laboratory soil ben was designed according to technical requirements using the COMPAS-3D program. An expression was derived to determine the required kinematic coefficient of the rotary tillage tool when conducting research on the laboratory soil bin. Dependences were established between the coefficient of kinematic mode and the number of teeth on the interchangeable gear sprockets (gear ratio) of the drive unit of the soil bin. The study identified the transmission settings corresponding to the investigated range of the coefficient of kinematic mode of operation for the selected tillage tools. Thus, the developed laboratory soil bin allows for research on optimizing the parameters and operating modes of actively driven rotary tillage tools. this will improve tillage quality, reduce energy requirements and increase overall soil tillage efficiency.

Key words: *actively driven rotary tillage tools, cylindrical ring tillage tool, knife tillage tool, tillage tool with covering element, laboratory soil bin, coefficient of kinematic mode.*

Introduction. Agricultural machines equipped with actively driven rotary tillage tools for surface tillage are highly promising in modern agriculture. They help reduce tractor wheel slipping and its negative impact on soil, while also expanding the suitable soil moisture range, ensuring high-quality treatment [1-3]. The energy intensity of the process and the quality of tillage depend on the design parameters and operating modes of these tillage tools.

Research in agricultural engineering science is inherently tied to experimental studies, which require specialized test facilities.

To develop and optimize implements and their tillage tools, both field and laboratory experiments are necessary. Soil bin is particularly valuable as they allow experiments to be conducted under controlled and repeatable conditions.

According to Godwin et al., designs of soil bin vary from large-scale type for full-size implement testing, to small automated systems [4]. An effective soil bin design should meet the following requirements:

1) Ensure homogeneous and isotropic soil conditions for testing both model and full-scale tillage implements as well as validating force prediction models;

2) Use commercially available equipment and instrumentation to minimize the need for specialist equipment;

3) Reduce capital costs and hand labor requirements for efficient operation.

Rosa and Wulfsohn have developed a monorail laboratory soil bin for the study of high-speed narrow tillage tools [5].

Yan et al. have developed a PLC-based control system for the laboratory soil bin for agricultural machinery [6].

Mardani et al. have developed a 23 m long, 2 m wide and 1 m deep laboratory soil bin with data acquisition system [7]. Test results showed that the data acquisition system could receive measured signals of force, velocity, moment and displacement in real time, display them on a monitor and record them on a computer.

The Federal State Budgetary Scientific Institution «Federal Scientific Agroengineering Center VIM» has developed a circular soil bin [8]. However, this soil bin design does not allow for the determination of forces acting on agricultural tillage tools.

The study of actively driven rotary tillage tools in a soil bin is important for understanding their operational patterns and interaction processes with soil. Research conducted by Nalavade P.P., Soni P., Salokhe V.M., Kumar S., Singh T.P., Upadhyay G. et al. has focused on actively driven disc tillage tools in soil bins [9-18].

However, to study various types of actively driven rotary tillage tools, it is necessary to develop a specialized laboratory soil bin that accounts for regulated operational parameters and modes. Therefore, the development of such a laboratory soil bin is both relevant and crucial for advancing agroengineering science.

The aim of this work is to enhance tillage efficiency through the research, development and application of actively driven rotary tillage tools.

Research objectives:

1) Development and design of the laboratory soil bin,

2) Investigation and optimization of coefficient of kinematic mode.

Materials and research methods. The research on developing the laboratory soil bin was conducted at the Nanjing Institute of Agricultural Mechanization, of the Graduate School of the Chinese Academy of Agricultural Sciences in cooperation with the Akhmet Baitursynuly Kostanay Regional University (Kazakhstan).

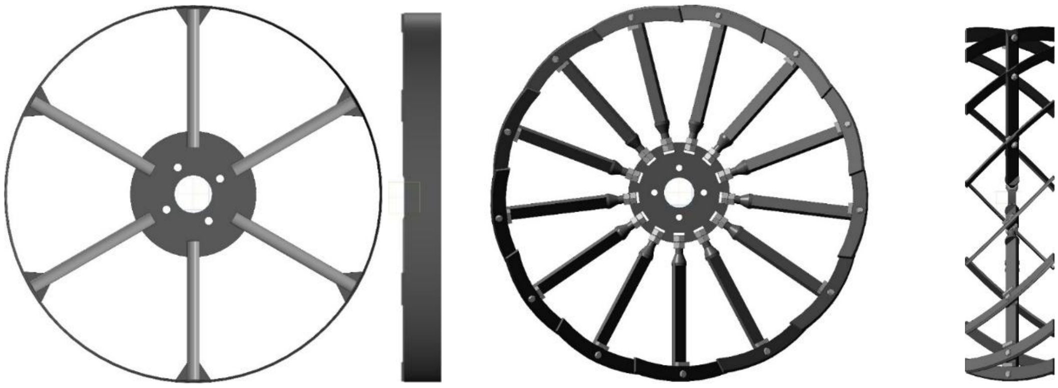
Three types of actively driven rotary tillage tools were selected for the study, Fig.1.

The rotary ring tillage tool is designed for weed cutting. It consists of a hub with a cylindrical ring rim attached by means of spokes, Fig.1a [19].

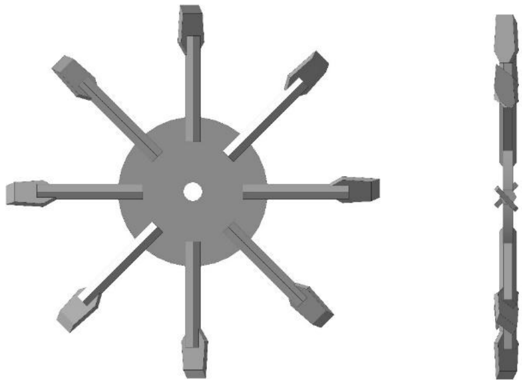
The rotary knife tillage tool is designed for pre-sowing tillage. It comprises a hub with attached spokes featuring elliptical-shaped cutting knife elements, Fig.1b [19].

The next one is a rotary tillage tool with covering elements for shallow autumn tillage for incorporation weed seeds into soil, Fig.1c. The elements are fixed to the hub by means of spokes at angles of inclination relative to both the vertical and horizontal plane of rotation [20].

During the research, the plane of rotation of these tillage tools is adjusted in two dimensions: deviated from travel direction by the angle of inclination α and from the vertical by the tilt angle β. The kinematic coefficient λ is varied across the range of 0.6 to 1.4 in increments of 0.2. The tillage tool radius is R_p=0.375 m.



a) b)



c)

a – ring tillage tool; б – knife tillage tool; в – tillage tool with covered elements
Figure 1 – Investigated actively driven rotary tillage tools

The design development of the laboratory soil bin for the studying actively driven rotary tillage tools was carried out in accordance with technical requirements and standards of the Unified Design Documentation System. Computer-aided design methods were employed using the COMPAS-3D software package. The resulting design documentation includes complete 3D models, general view drawings, detailed assembly unit drawings and specifications for the laboratory soil bin. These outputs form the complete basis for manufacturing the experimental setup.

The technological process of tillage performed by the specified rotary-type tillage tools operates as follows. The tillage tools rotate with active drive around their axis at an angular velocity ω in the counterclockwise direction while simultaneously moving with translational velocity. During operation, they penetrate the soil to the given tillage depth, loosening the soil and incorporating seeds while simultaneously cutting weeds, bringing them to the field surface and leveling the terrain.

Results and discussion. For conducting experimental studies of actively driven rotary tillage tools, a specialized laboratory soil bin was designed and developed, Fig.2. It consists of three mail components: a soil bin, a drive unit and a trolley assembly.

The soil bin is constructed as a containment box for filling soil and consists of perimeter fencing and lower cross beams. The trolley represents a welded steel structure comprising three rectangular frames of different sizes: large, medium and small. Four-wheel assemblies are welded to the large frame. The medium frame is positioned above the large frame and connected to it through linkage arms and pivot axes. The small frame incorporates cross beams designed for mounting the tillage tool and drive unit. This small frame connects to the medium frame through adjustable inclination mechanism that control its angle relative to the horizontal plane. Additionally, the assembly includes a separate mechanism for adjusting the inclination angle to the travel direction.

The inclination angle α to the travel direction can be adjusted in discrete increments and may be set to 40°, 70° and 90°. The angle of inclination from the vertical plane can be varied within the following ranges: -30° (backward tilt), 0° (vertical), +20° and +40° (forward tilt). The selected angles of attack are securely fixed using bolted connections. Fig.3 presents the kinematic scheme of the drive unit for the laboratory soil bin.

The technological process operates as follows. The electric motor 11 rotates the gear 14 of the toothed belt transmission, which drives the toothed belt 10. One end of the toothed belt 10 pulls the trolley 19 with the mounted tillage tool 9 and the drive mechanism mounted on it. The trolley 19 moves horizontally along the sliding bearings 13 of the wheels under the tension of the toothed belt 10. During this movement, the trolley 19 simultaneously rotates the unwinding drum 2 containing a pre-wound flexible cable 1, with one end fixed to a stationary shank. The rotation of the unwinding drum subsequently drives the rotary tillage tool 9 through the following transmission path: sprocket 3 on the drum axis, sprocket 4, sprocket set 5 on the intermediate axis, and sprocket set 6 on the tillage tool axis, all connected by chains 7, 8. This combined translational movement of the trolley and rotational movement of the rotary tillage tool facilitates the soil treatment process within the soil bin.

The translational speed of the trolley is adjusted by changing the sprockets set 5, while the circumferential speed of the tillage tool is modified using interchangeable sprocket set 6 mounted on the tillage tool axis. These adjustments enable precise selection of the required kinematic parameters for the tillage tool.

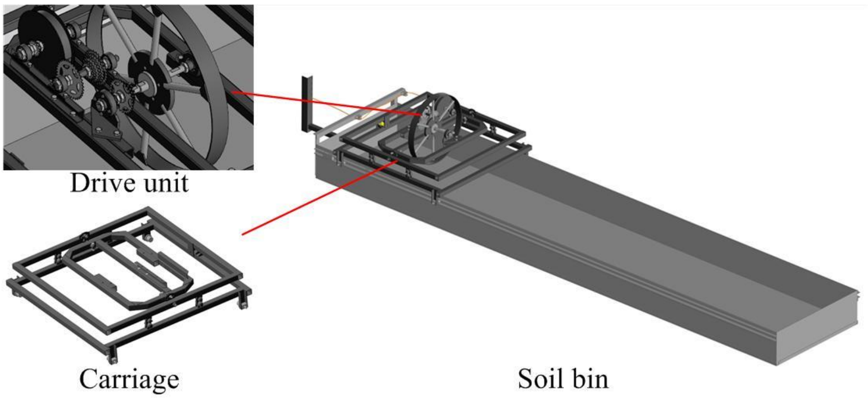
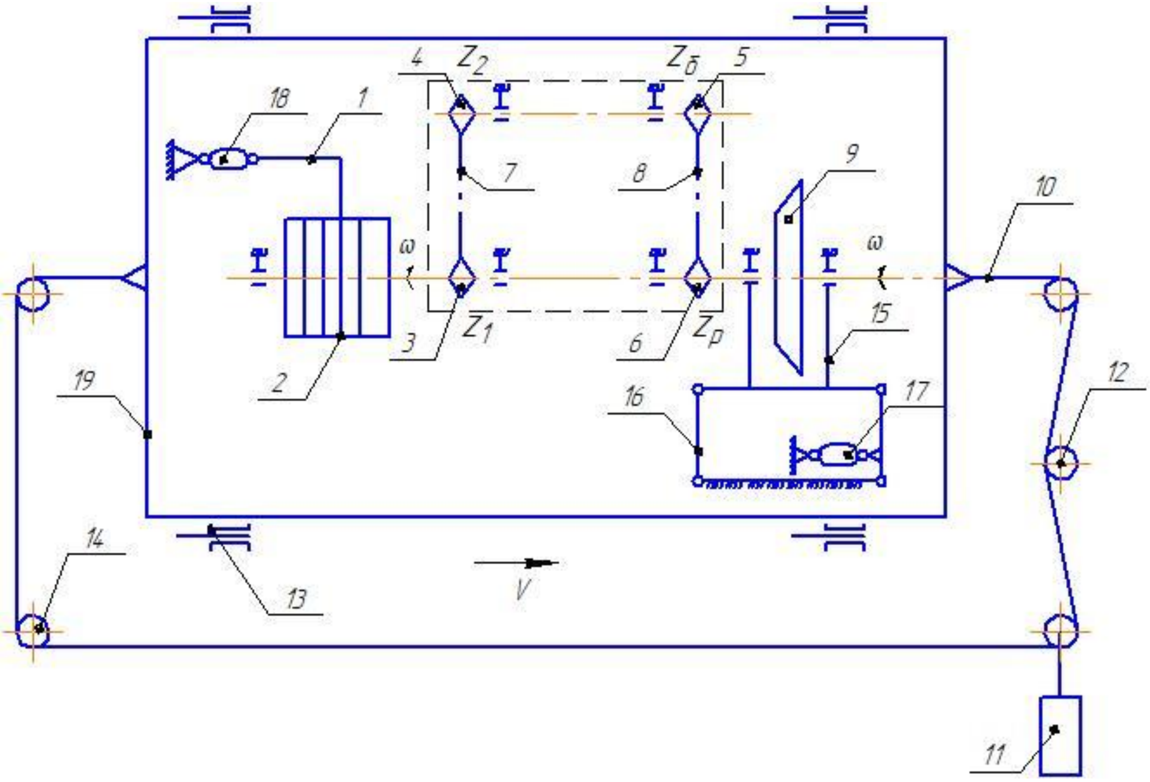


Figure 2 – General view of the laboratory soil bin



1 – flexible cable, 2 – unwinding drum, 3, 4, 5, 6 – sprocket assemblies, 7, 8 – chain transmissions, 9 – rotary tillage tool, 10 – toothed belt, 11 – electric motor, 12 – tension wheel, 13 –sliding bearings (wheel), 14 – the gear wheel, 15 – support; 16 – tensometric device with parallelogram mechanism; 17 – strain gauge (sensor) for draught resistance measurement, 18 – strain gauge (sensor) for torque measurement, 19 – trolley frame

Figure 3 – Kinematic scheme of the drive unit for the laboratory soil bin

For power parameter measurements, strain gauges (sensors) 17 and 18 are employed. The Draught resistance of the rotary tillage tool is measured by a strain gauge (sensor) mounted on a parallelogram mechanism 16 aligned with the trolley’s direction of movement. The investigated rotary tillage tool is attached to this parallelogram mechanism. Torque measurements are obtained from the strain gauge (sensor) 14 installed between the unwinding drum and the stationary shank on flexible cable.

The coefficient of kinematic mode of the rotary tillage tool is defined as the ratio of its circumferential velocity to its translational speed:

$$\lambda = V_o / V_e. \tag{1}$$

where, V_0 – circumferential velocity of the tillage tool;

V_e – translational velocity of the tillage tool.

Based on the λ value, the following operating modes are distinguished:

- $\lambda=0$, the tillage tool moves without rotation (passive mode).
- $\lambda>0$, the tillage tool moves with rotation (actively driven mode).

The translational and circumferential velocities of the rotary tillage tool are adjusted by altering the gear ratio through interchangeable sprocket set in the drive unit.

To establish the coefficient of kinematic mode, the gear ratios of all sprockets in the drive unit are calculated. Table 1 presents the numerical values of sprocket teeth counts used for calculating the coefficient of kinematic mode.

Table 1 – Sprockets teeth counts on the drive unit

Gear number	The number of teeth on the sprockets			
	Drive shaft (on the tillage tool axis)	Intermediate axis	Intermediate axis	Drive shaft (on the drum axis)
	Z_p	$Z_б$	Z_2	Z_1
1	14	14	48	15
2	16	16	–	–
3	18	18	–	–
4	22	20	–	–
5	24	22	–	–
6	28	24	–	–
7	–	28	–	–

The coefficient of the kinematic mode of operation is determined by the following formula according to the kinematic scheme of the drive mechanism of the laboratory soil bin:

$$\lambda = (z_{p\,б} \cdot r_p \cdot z_1) / (z_p \cdot r_{p\,б} \cdot z_2), \tag{2}$$

where, $z_{p\,б}$ – number of teeth on the unwinding drum shaft sprocket;

z_p – number of teeth on the rotary tillage tool shaft sprocket;

$r_{p\,б}$ – radius of the unwinding drum, m; ($r_{p\,б}$=0,11 m);

r_p – radius of the rotary tillage tool, m;

z_1, z_2 – the number of teeth of the corresponding sprockets.

Thus, the study has derived a formula for determining the required kinematic coefficient for actively driven rotary tillage tool during soil bin laboratory experiments.

The investigated range of coefficient of the kinematic mode for the developed rotary tillage tools is $0.4 \leq \lambda \leq 1.4$. This operational range was selected based on the optimization criteria including minimal energy consumption for tillage, reduced draught resistance, decreased rotational frequency of tillage tools and prevention of soil accumulation on tillage tool surfaces.

Table 2 presents the calculation results obtained using the formula (2).

The calculation identified operating modes both within and outside the studied range. In the table, green highlights indicate compliant range and red highlights indicate non-compliant range.

Figure 4 shows the relationship between the coefficient of kinematic mode λ and the number of teeth on the interchangeable drive sprockets $Z_б/Z_p$.

The graph similarly uses: green for compliant kinematic modes, red for non-compliant modes. For tillage tools with radius of R_p = 0.375 m, gears 1, 2 and 3 provide modes within the studied range. Gears 4, 5, and 6 exceed the range $\lambda \geq 1.4$.

Table 2 – Operating modes of the soil bin for the tillage tool

$Z_б$	Kinematic mode λ					
	Gear					
	1	2	3	4	5	6

	Z_p=16	Z_p=18	Z_p=20	Z_p=22	Z_p=24	Z_p=28
14	1.07	1.22	1.37	1.67	1.83	2.13
16	0.93	1.07	1.20	1.46	1.60	1.86
18	0.83	0.95	1.07	1.30	1.42	1.66
20	0.75	0.85	0.96	1.17	1.28	1.49
22	0.68	0.77	0.87	1.07	1.16	1.36
24	0.62	0.71	0.80	0.98	1.07	1.24
28	0.53	0.61	0.68	0.84	0.91	1.07

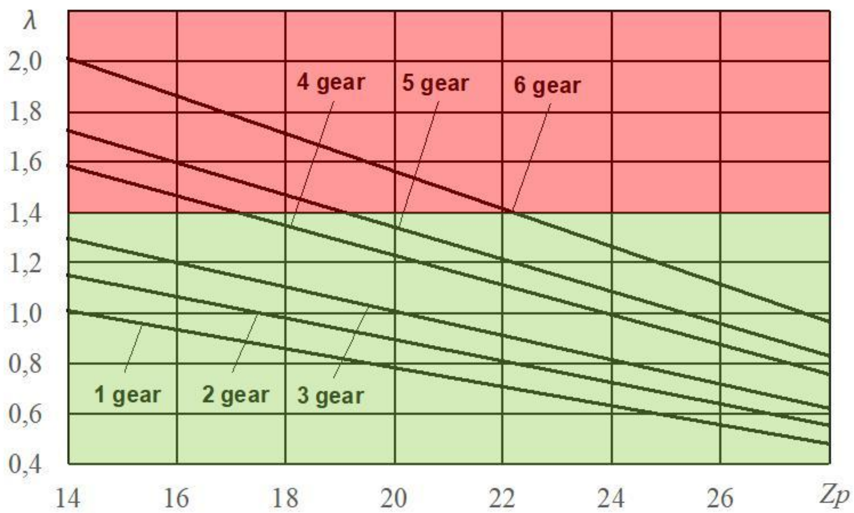


Figure 4 – Dependence of the coefficient of kinematic mode λ on the number of teeth of interchangeable drive sprockets $Z_б/Z_p$

Thus, the study successfully identified values corresponding to the studied range of the coefficient of kinematic mode for actively driven rotary tillage tools.

Conclusions. Agricultural implements with actively driven rotary tillage tools show significant promise in modern agriculture, where energy efficiency and tillage quality depend on their design parameters and operating modes.

A specialized laboratory soil bin has been developed to conduct experimental studies of soil interaction with actively driven rotary tillage tools. This facility enables precise adjustment of inclination angle to the travel direction, tilt angle from vertical plane, coefficient of kinematic mode and determination of both quality parameters and energy performances during operation.

The study has derived a mathematical expression for determining the required coefficient of kinematic mode of actively driven rotary tillage tool during soil bin laboratory experiments. The research has revealed relationship between the coefficient of the kinematic mode and the number of teeth on the interchangeable drive sprockets (gear ratio). Furthermore, specific transmission configurations corresponding to the studied operational range of the coefficient of kinematic mode have been identified for the developed tillage tools.

The developed laboratory soil bin enables comprehensive investigation of actively driven tillage tools, facilitating optimization of design parameters and operational of rotary actively driven tillage tools, significant improvement in tillage quality, substantial reduction in energy requirements, consequently, enhanced soil cultivation efficiency.

The work was conducted as part of an internship under the «Bolashak» international scholarship program within the «500 scientists» project.

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ТҮЙІН

Белсенді жетекті айналмалы жұмысшы бөліктері бар топырақ өңдеу машиналары ауыл шаруашылығында перспективалы болып табылады. Олар заманауи егіншілікте ғылыми зерттеулер мен өндірістік қолданудың нысанына айналды. Алайда, оларды одан әрі жетілдіру олардың топырақпен өзара әрекеттесу процесінің аз зерттелуімен шектеледі. Зерттеудің мақсаты белсенді жетекті айналмалы жұмысшы бөліктерін зерттеу, әзірлеу және қолдану арқылы топырақты өңдеу тиімділігін арттыру болып табылады. Зерттеу үшін белсенді жетекті айналмалы жұмысшы бөліктердің әзірленіп жатқан 3 түрі таңдалды: цилиндрлік айналмалы жұмысшы бөлік, пышақты жұмысшы бөлік және айналмалы қалақты жұмысшы бөлік. Мақалада аталған жұмысшы бөліктердің топырақпен өзара әрекеттесуіне эксперименттік зерттеулер жүргізу үшін зертханалық қондырғыны әзірлеу бойынша жұмыс нәтижелері келтірілген. Зерттеу барысында өңдеу бұрышы сатылы түрде реттеліп, 40º, 70º және 90º болуы мүмкін. Тігінен көлбеу бұрыш – 30º (артқа), 0º, +20º және +40º (алға) аралығында өзгеруі мүмкін. Зерттеу үшін кинематикалық жұмыс режимі коэффициенті $0,6 \leq \lambda \leq 1,4$ шегінде диапазоны таңдалды. Қондырғыны құрылымдық әзірлеу «КОМПАС-3D» бағдарламасын пайдалана отырып, техникалық талаптарға сәйкес жүргізілді. Топырақ арнасының зертханалық қондырғысында зерттеу жүргізу барысында айналмалы жұмысшы бөліктің қажетті кинематикалық коэффициентін таңдау үшін өрнек алынды. Кинематикалық жұмыс режимінің коэффициенті қондырғы жетегінің ауыспалы беріліс жұлдыздарының тістерінің санына (беріліс қатынасы) байланысты. Зерттеу нәтижелері бойынша әзірленетін жұмысшы бөліктердің кинематикалық жұмыс режимі коэффициентінің зерттелетін диапазонына сәйкес берілістер анықталды. Осылайша, топырақ арнасының әзірленген зертханалық қондырғысы белсенді жетекті айналмалы жұмысшы бөліктердің шарқы өлшемдері мен жұмыс режимдерін негіздеу және таңдау бойынша зерттеулер жүргізуге мүмкіндік береді, онда топырақ өңдеу кезінде сапасының жақсаруы және энергия шығындарының төмендеуі қамтамасыз етіледі, демек, өңдеу тиімділігі артады.

РЕЗЮМЕ

Почвообрабатывающие машины с приводными роторными почвообрабатывающими орудиями являются перспективными в сельском хозяйстве. Эти орудия стали предметом научных исследований и промышленного применения в современном сельском хозяйстве. Однако их дальнейшее совершенствование ограничивается недостаточно изученным процессом их взаимодействия с почвой. Целью исследования является повышение эффективности процесса обработки почвы за счет исследования, разработки и применения активно приводимых роторных почвообрабатывающих орудий. Для исследования были выбраны три типа активно приводимых роторных почвообрабатывающих орудий: цилиндрическое кольцевое почвообрабатывающее орудие, ножевое почвообрабатывающее орудие и роторное почвообрабатывающее орудие с заделывающими элементами. В статье представлены результаты работы по разработке лабораторного почвенного бункера для проведения экспериментальных исследований взаимодействия почвы и почвообрабатывающих орудий. В ходе исследования угол наклона от направления движения может быть ступенчато отрегулирован до 40°, 70° и 90°. Угол наклона от вертикальной плоскости может изменяться в пределах от -30° (назад), 0° (по вертикали), +20° и +40° (вперед). Коэффициент кинематического режима исследовался в диапазоне $0,6 \leq \lambda \leq 1,4$. Лабораторный почвенный бункер был спроектирован согласно техническому заданию с использованием программы КОМПАС-3D. Выведено выражение для определения необходимого кинематического коэффициента роторного почвообрабатывающего орудия при проведении исследований на лабораторном почвенном бункере. Установлены зависимости между коэффициентом кинематического режима и числом зубьев сменных зубчатых колес (передаточным числом) привода почвенного бункера. В результате исследования определены параметры трансмиссии, соответствующие исследуемому диапазону коэффициента кинематического режима работы для выбранных почвообрабатывающих орудий. Таким образом, разработанный лабораторный почвенный бункер позволяет проводить исследования по оптимизации параметров и режимов работы активно-приводных роторных почвообрабатывающих

орудий, что позволит улучшить качество обработки почвы, снизить энергозатраты и повысить общую эффективность обработки почвы.