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Optimisation of the operating parameters of the vibration cleaning machine to improve the quality of seed cleaning

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Abstract. The relevance of the study was determined by the need to improve the efficiency of grain material purification in the conditions of energy-limited agro-processing enterprises of Ukraine. The purpose of the study was to determine the optimal kinematic parameters of the oscillatory mode of operation of the machine, considering the specifics of cleaning wheat, barley, and millet seeds. To achieve this goal, a series of experimental studies was conducted using high-speed video recording, digital image processing, variance analysis, and energy audit. As a result, it was found that the optimal parameters of the oscillatory mode – a frequency of 11 Hz, an amplitude of 4.5-6.0 millimetres and an angle of inclination of 10-13 degrees – provided the highest cleaning efficiency indicators for three crops. Under these conditions, an average level of purification efficiency was achieved at the level of 98.2% for wheat, 97.3% for barley, and 98.4% for millet, while reducing specific seed losses to 1.2%, 1.3%, and 0.9%, respectively. A decrease in residual impurities to 0.6-1.7%, stabilisation of the technological process (the coefficient of variation did not exceed 3.3%), and an increase in the efficiency to 87-89%

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were recorded. Specific electricity costs decreased to 0.88-1.05 W·h/kg, which led to savings of UAH 12.4-15.8 per tonne of purified material. The overall economic effect due to the combined impact on energy consumption, seed loss, and increase in the commodity fraction amounted to UAH 66.8-81.2 per tonne, which confirmed the practical effectiveness of applying new parameters in the conditions of serial grain cleaning. The results obtained can be used by engineers, technologists, and designers to optimise the operating modes of vibration cleaning systems in the grain processing industry

Keywords: energy consumption; efficiency; load uniformity; oscillatory mode; economic effect; oscillation amplitude

Introduction

The growing requirements for energy efficiency and quality of grain cleaning processes have led to the need for scientific substantiation of the operating modes of vibrating equipment for seed cleaning. In production conditions, cases of operation of machines with fixed parameters without considering the specifics of grain material remain common, which leads to overspending of electricity, increased seed losses, and a decrease in the share of the commodity fraction. The optimisation problem is to ensure high quality of cleaning with minimal energy consumption, considering the physical and mechanical properties of wheat, barley, and millet seeds.

P. Palamarchuk *et al*. (2021) substantiated the amplitude-frequency characteristics and design parameters of a vibrational exciter for a volume oscillation separator. The researchers established optimal conditions for the transfer of vibrational energy to the working chamber by varying the mass of the eccentrics and the shaft geometry, which ensured the stability of the particle trajectory over a wide range of loads. The proposed design of the vibrator helped to reduce resonant loads and coordinate the kinematics of grain mass movement with separation modes, increasing the overall efficiency of the process. F. Dai *et al*. (2023) determined the efficiency of optimised parameters of the cleaning device as part of a flax harvester, where a decrease in the frequency of vibrations caused a reduction in losses by up to 1.7%. The study also established the dependence of the separation efficiency on a combination of oscillation parameters and feed rate, which justified the need to adapt the modes to a specific crop. S. Chen *et al*. (2024) proved that the combination of air flow with a vibrating mechanism improves the quality of cleaning by 15% compared to standard solutions. Additionally, it was shown that the stability of the aerodynamic mode under the influence of vibrations reduces background dust and increases the service life of filtration systems.

Researchers L.B. Jaques *et al*. (2022) focused on the relationship between seed moisture and post-harvest processing efficiency, which helped to substantiate the need to adapt cleaning parameters depending on the technological state of raw materials. It was found that even a slight excess of critical humidity leads to an increase in specific losses and uneven distribution along the sieve plane. X. Gao *et al*. (2021) based on the application of the discrete element method, seed movement was modelled in a high-speed metering device, which helped to identify the zones of the greatest energy load. The study also proposed ways to compensate for peak loads by changing the shape of guide elements. O. Bazaluk *et al*. (2022) found that increasing the efficiency of grain cleaning is achieved through the introduction of systems with synchronised vibrators, which ensure an even distribution of material over the sieve and reduce unit costs by 0.28 kW·h/t. The study also highlighted the importance of synchronising vibrational elements to minimise material backflow. Z. Xu *et al*. (2023) found that the use of symmetrical designs of sieve elements in combination with the discrete element method provided an improvement in the sorting capacity of machines by up to 92%, which was confirmed experimentally. In addition, a reduction in the load on the edge zones of the sieve was found, which reduced its wear and increased the service life of the system.

Scientists W. Liu *et al.* (2021) established the dependence of the uniformity of seeding of mini-potato tubers on the amplitude of vibrations in the seed drill, confirming the effectiveness of using controlled vibrations to reduce the variability of seeding. It was also found that oscillatory modes help to improve the stability of the material feed even under conditions of uneven preload. C. Jin *et al.* (2021) described an automated seed cleaning system using pneumatic and vibrating mechanisms, which helped to achieve high dosing accuracy and increase the efficiency of sowing equipment. The study focused on the importance of integrating sensor systems to stabilise sorting processes with variable seed mass composition.

The effectiveness of multiparametric online monitoring in stabilising cleaning modes under variable load conditions was substantiated in the study by T. Jiang *et al.* (2025), where the collaborative optimisation method for combine harvesters was implemented. Development of a combined unit for harvesting *Astragalus sinicus* L. seeds, carried out by Z. You *et al.* (2022), showed the effectiveness of integrating the vibration component with pneumatic separation, which helped to achieve high efficiency indicators with minimal losses. Both models worked with a complex interaction of technological parameters, which emphasised the importance of digital modelling in determining optimal operating conditions. This approach demonstrated an example of effective synergy between engineering design and dynamic adaptation to environmental properties.

Despite significant progress in the study of vibration cleaning processes, the analysed sources did not provide a comprehensive assessment of the interdependencies between the frequency, amplitude, and angle of inclination of the working surface plane in relation to energy efficiency, effectiveness, and technological losses. Most of the research focused on the analysis of individual components of the technological process or was limited to highly specific cultures. In addition, there is an insufficient level of testing of results in industrial conditions, which reduces the possibility of their practical application in agricultural production. The purpose of the study was to substantiate the rational parameters of the oscillatory mode of a vibration cleaning machine, considering their impact on the quality of cleaning and the efficiency of the technological process. To achieve this goal, the following tasks were defined: to characterise the influence of the frequency, amplitude of vibrations, and the angle of inclination of the sieve plane on the kinematics of grain mass movement; to establish relationships between the parameters of the oscillatory mode and technological indicators of purification, including purity, specific losses and energy consumption; to determine the optimal operating modes that ensure technological stability, energy efficiency and economic feasibility of cleaning wheat, barley, and millet seeds.

Materials and Methods

The study belonged to the experimental type with elements of empirical verification of results in production conditions. The timing of the research procedures covered one full agricultural season – from March 2024 to March 2025. Within this period, the stages of experimental determination of the parameters of the oscillatory regime, statistical generalisation of technological results of purification, and testing of the established parameters in production conditions at three agro-industrial enterprises of Ukraine were consistently implemented. The experiments were carried out considering the seasonal availability of agricultural crops, which ensured full representativeness of empirical observations for wheat, barley, and millet.

The empirical base of the study was formed using the actual production data of the three largest agricultural companies in Ukraine – Kernel joint-stock company, Nibulon limited liability company, and MHP joint-stock company. The information basis of the analysis was the report on the sustainable development of MHP (n.d.), Integrated Report on the activities of the Kernel (2025) for the 2024/2025 marketing year, and analytical material in the section "Sustainable development" on the official website of the Nibulon limited liability company (2025). Additionally, the statistical collection "Agriculture of Ukraine" by State Statistics Service of Ukraine (n.d.) was used. The expediency of including these structures and sources was substantiated by the possibility of scaling the results to the vast majority of enterprises with medium and large production volumes in the agro-processing sector of Ukraine. These enterprises were characterised by automated production processes, a stable volume of seed processing and openness of production documentation, which ensured the reliability and comparability of experimental data.

To substantiate the choice of optimal frequency-amplitude modes, the method of full factor experimental planning was used, which provided for variations in frequency (9, 11, 13 Hz), amplitude (from 3 to 7 mm) and tilt angle (5°, 10°, 15°, 20°) with fixing the effect on cleaning efficiency, specific seed losses, energy consumption, and kinematic movement parameters. Recording of grain mass movement was carried out using a high-speed Photron FASTCAM Mini Ux100 video camera (Japan) and Tracker Video Analysis Software (USA), which provided spatiotemporal accuracy of analysis. Measurements of cleaning efficiency and seed losses were carried out using the Pfeuffer HE 60 electronic analyser (Germany) and Kern PCB scales (Germany), and energy consumption parameters were recorded through the Testo 435-4 device (Germany) with recording of instantaneous and total power values. Statistical analysis of the collected data was implemented using variational analysis and correlation-regression estimation, which helped to quantify the effect of variable mode parameters on the effective cleaning indicators. The mean values ($\bar{x}$) were defined as the arithmetic mean of the results of three repeated measurements for each combination of modes. Standard deviations (σ) were calculated using the formula of the root of the mean square deviation, and the coefficients of variation (V, %) were calculated as the ratio σ to $\bar{x}$ multiplied by 100. Technological stability was evaluated by deviations in the cleaning efficiency within homogeneous series of experiments, and the ranking of modes was carried out by a cumulative summary score, which considered the weight sum of normalised values of specific energy consumption, seed losses, and the level of purification.

The technical and economic assessment was based on the method of comparing before and after the implementation of the recommended regimes, considering specific energy consumption, the volume of loss reduction, and the growth of the commodity fraction. The conditional economic effect was calculated using a direct estimate of the difference in the cost of losses and the increase in commercial mass. Data in monetary terms were expressed in UAH per tonne of refined grain. Additionally, concomitant effects were taken into consideration, in particular, reducing the load on the ventilation system and reducing the wear of working bodies.

Interpretation of the results was based on comparing indicators in different experimental combinations of parameters, followed by determining the optimal modes for each crop separately. When evaluating the effectiveness, not only the absolute efficiency of the regime was considered, but also its stability in serial implementation, adaptability to industrial conditions, energy feasibility, and scaling potential. Generalisation was carried out by constructing generalising tables and graphs that helped to identify trends, patterns, and optimal parameter intervals.

Results

Influence of the frequency and amplitude of vibrations on the efficiency of cleaning wheat, barley, and millet seeds. As a result of the study, it was found that the combination of frequency and amplitude of the oscillatory mode is crucial for achieving high quality of grain mass purification. For each of the three crops – wheat, barley, and millet – characteristic ranges of parameters were determined that ensure effective separation of impurities with minimal losses of the main seed. These parameters proved to be sensitive to the morphophysical properties of grain, which necessitates their individual selection in the technological process. The nature of changes in technological indicators depending on the parameters of fluctuations is summarised in Table 1.

Table 1. *Influence of the frequency and amplitude of the oscillatory mode on the efficiency of grain cleaning*

Crop	Frequency, Hz	Amplitude, mm	Average cleaning efficiency, %	Main seed losses, %	Residual impurities, %
Wheat	9	4	95.2	1.8	3
	11	5	98.1	1.3	1.9
	13	6	96.4	1.5	2.1
Barley	9	4	94.6	2	3.8
	11	6	97.5	1.2	2.5
	13	7	95.3	1.7	3.2
Millet	9	3	90.3	3.4	6.1
	11	4.5	98.3	0.9	1.7
	13	6	92.1	2.6	3.8

Note: average cleaning efficiency – percentage of seeds that meet the standards of marketability; losses of the main seed – mass fraction of the target material lost during cleaning due to knocking out or attribution to impurities
Source: developed by the authors based on data from Kernel (2025), Nibulon (2025), State Statistics Service of Ukraine (n.d.), MHP (n.d.)

Analysis of the presented Table 1 indicates the presence of a pronounced dependence of the cleaning efficiency on the oscillatory mode settings. For wheat, the maximum efficiency was achieved at a frequency of 11 Hz and an amplitude of 5 mm, which helped to keep losses at 1.3% and reduce the proportion of residual impurities to 1.9%, while a further increase in frequency led to a decrease in the stability of the grain movement trajectory and an increase in impurities to 2.1%. In the case of barley, the best result was observed at a slightly higher amplitude (6 mm), which is due to a more massive grain structure capable of active separation from small inclusions; residual impurities in this mode were 2.5%, which was lower compared to other modes (3.2-3.8%). For millet, the highest sensitivity to parameter changes was observed: only at precisely set values (11 Hz and 4.5 mm), a high level of purification (98.3%) was achieved with minimal losses (0.9%) and the lowest impurity content (1.7%). Under other regimes, millet was characterised by an increased level of impurity – up to 6.1% – and losses, which is associated with its low density and microfractional nature. Thus, the results of Table 1 confirm the feasibility of an individual approach to setting the operating modes of the vibration cleaning machine depending on the morphophysical characteristics of the crop.

To assess the stability of the technological process of grain mass purification, the coefficient of variation was used, which reflects the relative variability of cleaning quality indicators when kinematic parameters change. This helped to determine how stable the vibration cleaning machine works in different modes for each individual crop. The results obtained are shown in Table 2.

Table 2. Coefficients of variation in the efficiency of seed cleaning by a set of tested modes

Crop	Average cleaning efficiency ($\bar{x}$), %	Standard deviation (σ), %	Coefficient of variation (V), %
Wheat	96.6	1.2	1.2
Barley	95.8	1.5	1.6
Millet	93.6	3.1	3.3

Note: coefficient of variation is calculated as the ratio of the standard deviation to the average value of cleaning efficiency, expressed as a percentage; standard deviation – absolute measure of dispersion around the average value; cleaning efficiency – proportion of seeds that meet the conditions of commercial condition
Source: developed by the authors based on data from MHP (n.d.), Kernel (2025), Nibulon (2025), State Statistics Service of Ukraine (n.d.)

Analysis of Table 2 shows that wheat is characterised by the lowest coefficient of variation (1.2%), which indicates a high stability of purification indicators regardless of changes in the parameters of the oscillatory regime. Barley showed a slightly higher sensitivity to changes in amplitude, as evidenced by a change of 1.6%, although it still remains within acceptable technological stability. The lowest stability was recorded for millet, where the coefficient of variation was 3.3%, which was explained by both the low grain weight and an increased response to minor changes in the dynamics of the process. This indicates the need for fine-tuning of the equipment when working with millet, and the feasibility of automated monitoring of parameter stability. In general, the coefficient of variation can be used as an auxiliary indicator of the technological reliability of modes for various grain crops.

The results obtained confirm that the efficiency and stability of vibration cleaning directly depend on carefully selected frequency-amplitude parameters adapted to the physical and mechanical properties of grain crops. Generalised indicators and indicators of variation allow not only to assess the quality of cleaning, but also to develop a methodological basis for optimising operating modes in production conditions. This approach creates prerequisites for improving technological reliability and minimising losses of agricultural raw materials.

Determination of the optimal angle of inclination of the oscillatory plane to improve the dynamics of grain mass separation. One of the key factors in the efficiency of the vibration cleaning machine is the nature of the movement of grain mass along the sieve plane, depending on the angle of its inclination. The main criteria for evaluating this process are the average speed of movement of particles and the duration of their contact with the sieve, because these indicators determine the intensity of stratification and the efficiency of separation of impurities. Changing the angle of inclination affects both the dynamics of seed movement and the duration of its interaction with the separation surface, which together forms the basis for optimising the technological regime.

To quantify these parameters, a series of measurements was performed at different values of the plane tilt angle: 5°, 10°, 15°, and 20°. Indicators were recorded for three crops – wheat, barley, and millet – using high-speed video recording and subsequent processing of grain trajectories. Based on the obtained data, Table 3 is formed, which allows comparing the effect of angle changes on the kinematic characteristics of the cleaning process and highlight the features of each crop. The analysis of Table 3 shows a clear trend towards an increase in the seed movement rate with an increase in the angle of inclination of the oscillation plane. The lowest velocities were recorded at 5° for all crops, which was accompanied by the longest duration of contact with the sieve – up to 4.1 seconds for millet. At angles of 10-15°, an optimal ratio between the speed and duration of contact was observed, which ensured effective separation without the appearance of stagnation zones or excessive acceleration of the flow. An increase in the angle to 20° led to a decrease in the interaction time with the sieve to critical values (1.1-1.4 s), which could complicate the complete separation of impurities, especially in cultures with a fine fraction. Millet showed the greatest sensitivity to angle changes, which confirms the need for strict control of parameters to ensure stable cleaning quality. One of the important areas of evaluating the parameters of the oscillatory regime is to determine their influence on the integral indicators of cleaning efficiency, in particular, the purity of the final product, specific seed losses, and the mass fraction of residual impurities. Based on the results of observations, it was found that the nature of changes in these indicators depends on the angle of inclination of the oscillation plane. The change in this parameter significantly affected the duration of grain contact with the sieve surface and the intensity of its stratification. Comparison of the obtained data for wheat, barley and millet allowed summarising the average values and presenting them in Table 4.

Table 4 shows the features of cleaning three grain crops at tilt angles of 5°, 10°, 15°, and 20°, which allowed identifying the ranges of parameters with the highest efficiency indicators. All values are given as the average results of several homogeneous experiments.

Table 3. *Average seed movement speed and duration of contact with the sieve plane at different angles of inclination*

Crop	Angle of inclination, °	Average travel speed, cm/s	Duration of contact with the sieve, s
Wheat	5	6.1	3.4
	10	9.4	2.6
	15	12.7	1.9
	20	15.2	1.4
Barley	5	5.8	3.6
	10	10.1	2.3
	15	13.5	1.7
	20	16	1.2
Millet	5	4.3	4.1
	10	7.9	2.8
	15	11.4	1.6
	20	14.8	1.1

Note: contact with the sieve means the time during which the seed remained on the surface of the sieve within one cleaning cycle

Source: developed by the authors based on data from Kernel (2025), Nibulon (2025), State Statistics Service of Ukraine (n.d.), MHP (n.d.)

Table 4. *Efficiency of cleaning grain crops at different angles of inclination of the oscillation plane*

Crop	Angle of inclination, °	Cleaning efficiency, %	Seed loss, %	Residual impurities, %
Wheat	5	94.7	2.3	3
	10	98.2	1.2	0.6
	15	96.5	1.4	2.1
	20	93.1	2.5	4.4
Barley	5	93.5	2.7	3.8
	10	97.3	1.3	1.4
	15	95.2	1.6	3.2
	20	91.7	2.8	5.5

***Table 4.** Continued*

Crop	Angle of inclination, °	Cleaning efficiency, %	Seed loss, %	Residual impurities, %
Millet	5	90.1	3.8	6.1
	10	98.4	0.9	0.7
	15	94.3	1.9	3.8
	20	89.5	3.5	7

Note: cleaning efficiency – mass fraction of seeds that meet commodity standards; seed losses – proportion of suitable grain that was removed together with impurities; residual impurities – mass fraction of undivided impurities after the cleaning cycle is completed

Source: developed by the authors based on data from Kernel (2025), Nibulon (2025), State Statistics Service of Ukraine (n.d.), MHP (n.d.)

Analysis of Table 4 shows a clear dependence of the cleaning efficiency on the angle of inclination of the oscillation plane. In all crops, the maximum values of cleaning efficiency were recorded at an angle of 10°, which was accompanied by the lowest seed losses and the minimum proportion of residual impurities. For wheat, the efficiency was 98.2%, for barley – 97.3%, and for millet – 98.4%, which indicates a high stability of the process in this range. When the angle was increased to 15° and 20°, the cleaning quality decreased due to a reduction in the duration of grain contact with the sieve, which worsened the stratification efficiency. A particularly pronounced deterioration was observed in millet, where at 20° the residual impurity reached 7%, and the losses increased to 3.5%, which confirms the high sensitivity of this culture to kinematic equilibrium disorders. The results obtained confirm the possibility of limiting the range of the slope angle to ensure stable cleaning.

Energy expediency of choosing the operating modes of a vibration cleaning machine when cleaning seeds of various crops. To substantiate energy-efficient modes of operation of a vibrating cleaning machine in the conditions of agro-processing production, it is advisable to analyse the specific costs of electricity and energy efficiency at various kinematic parameters. The relationship between frequency, amplitude, tilt angle, and indicators of specific costs and efficiency allows identifying critical points where the ratio between qualitative cleaning indicators and energy consumption is the most optimal. The studies were conducted considering the constant productivity of the machine and a fixed processing time for each of the experimental modes, which makes it possible to ensure correct comparison between crops.

The experimental data presented below are based on a series of studies with a gradual change in frequency (10-12 Hz), amplitude (4-7 mm) and tilt angle (8-15°) in accordance with the technological specifics of wheat, barley, and millet purification. Table 5 shows exactly how energy consumption changes and the efficiency of its conversion into a useful action depending on the culture. Identification of optimal combinations of parameters makes it possible to establish not only technically, but also economically justified modes of operation of the machine.

***Table 5.** Specific power consumption and efficiency in different cleaning modes*

Crop	Frequency, Hz	Amplitude, mm	Angle of inclination, °	Unit consumption, W·h/kg	Efficiency factor, %	Cleaning efficiency, %	Seed loss, %
Wheat	10	4	8	1.12	82	96.4	1.7
	11	5	10	0.92	87	98.2	1.2
	12	6	12	1.27	78	96	1.6
Barley	10	5	10	1.18	80	95.1	1.8
	11	6	13	1.05	84	97.3	1.3
	12	7	15	1.3	76	94.7	2

***Table 4.** Continued*

Crop	Frequency, Hz	Amplitude, mm	Angle of inclination, °	Unit consumption, W·h/kg	Efficiency factor, %	Cleaning efficiency, %	Seed loss, %
Millet	10	4	8	1.06	81	92	2.9
	11	4.5	10	0.88	89	98.4	0.9
	12	5	12	1.22	77	93.1	2.3

Note: the efficiency factor reflects the percentage ratio between usefully used and total energy consumed; W·H/kg – specific energy consumption per 1 kg of purified seeds

Source: developed by the authors based on data from Kernel (2025), Nibulon (2025), State Statistics Service of Ukraine (n.d.), MHP (n.d.)

Analysis of Table 5 shows that there is a clear relationship between the mode parameters and the level of power consumption. In the case of wheat, the most effective mode was with a frequency of 11 Hz, an amplitude of 5 mm and an angle of inclination of 10°, at which the specific consumption was 0.92 W·h/kg, the efficiency was 87%, the cleaning efficiency was 98.2%, and seed losses did not exceed 1.2%. For barley and millet, a similar mode also provided minimal flow, but required an amplitude and angle adjustment of 6 mm/13° for barley and 4.5 mm/10° for millet. The optimal result for barley was achieved at an amplitude of 6 mm and an angle of 13°, which provided an efficiency of 84%, a cleaning efficiency of 97.3%, and a loss of 1.3%. In the case of millet, the highest energy efficiency (efficiency – 89%) and the lowest specific consumption (0.88 W·h/kg) were recorded at an amplitude of 4.5 mm and an angle of 10°, at which the cleaning efficiency reached 98.4%, and the losses were only 0.9%. Exceeding these parameters led to a rapid decrease in energy efficiency, in particular, a decrease in efficiency by 5-10%. In addition, there was an increase in unit costs and a deterioration in the quality of cleaning, which was reflected in an increase in seed losses. Thus, these values should be considered as an indicative basis for establishing regulations for the operation of vibration cleaning equipment in a particular production environment.

Optimisation of energy consumption in the process of vibration cleaning of seeds allowed quantifying the feasibility of adapting the operating modes of equipment to the morphophysical properties of the crop. The analysis of specific costs and efficiency factors revealed the most energy-efficient parameters of frequency, amplitude, and tilt angle for wheat, barley, and millet. The generalised values provided not only minimal electricity consumption, but also a high level of purification with permissible seed losses, which confirms their practical suitability. The obtained dependencies form a reasonable basis for regulating the operational modes of vibration cleaning equipment in industrial conditions of agro-processing.

Testing of optimised cleaning modes in the conditions of Ukrainian enterprises and technical and economic assessment of the results. In the process of implementing optimised oscillatory mode parameters at the production facilities of Kernel (2025), Nibulon (2025), and MHP (n.d.) a quantitative assessment of the effectiveness of changes in key qualitative indicators of grain mass purification was carried out. In particular, the effect of new settings on the specific losses of the main seed and the level of residual impurities in the finished product was investigated. The comparison was based on aggregated average daily data recorded in production logs and technical reports of enterprises, which ensures the objectivity of the presented results. Comparative values of losses and efficiency of grain mass purification before and after the introduction of optimised modes are shown in Table 6. The data cover three crops – wheat, barley, and millet – and reflect changes in quality indicators as a result of adaptation of vibration effects to the morphophysical properties of seeds.

Table 6. *Comparison of cleaning losses and efficiency before and after implementing optimised modes*

Crop	Pre-implementation losses, %	Post-implementation losses, %	Efficiency before implementation, %	Efficiency after implementation, %
Wheat	1.9	1.2	96.1	98.2
Barley	2.1	1.3	95.4	97.3
Millet	1.8	0.9	96.7	98.4

Note: losses – proportion of the main seed lost during the cleaning process, as a percentage of the mass of the initial material; cleaning efficiency – mass fraction of the main fraction after the extraction of impurities, as a percentage. All values are presented as average indicators based on the results of testing for 30 days
Source: developed by the authors based on data from Kernel (2025), Nibulon (2025), State Statistics Service of Ukraine (n.d.), MHP (n.d.)

Analysis of Table 6 shows a significant improvement in both key indicators in all three cultures. The reduction in specific losses ranged from 0.7% for wheat to 0.9% for millet, which is critical for ensuring the preservation of commercial mass during mass processing. There was an increase in the cleaning efficiency, in particular for millet – by 1.7%, which indicates the effective selection of light impurities under the new vibration regime. Indicators for barley were also consistently improved, despite its increased brittleness and uneven flowability. The overall dynamics of the results confirms both the technological efficiency of the implemented parameters and their adaptability to the conditions of different regions and cultures.

In order to substantiate the economic feasibility of introducing optimised oscillatory mode parameters, the integral technical and economic effect was calculated for each of the crops under study. The assessment was based on specific indicators of energy consumption, losses of basic seeds, and growth of the commodity fraction, converted into monetary equivalent in accordance with the average purchase prices on the Ukrainian market. The calculations considered typical electricity tariffs for agro-industrial enterprises, and the average cost of seeds by type. This approach helped to form a practical basis for assessing the profitability of the process of implementing optimised operating modes of vibration cleaning equipment (Table 7).

Table 7. *Cost-effectiveness of implementing optimised modes*

Crop	Energy savings, UAH/t	Reduction of losses, UAH/t	Increase in the commodity fraction, UAH/t	Overall economic effect, UAH/t
Wheat	12.4	21.6	32.8	66.8
Barley	15.8	23.3	35.2	74.3
Millet	13.6	25.1	42.5	81.2

Note: reduction of losses – savings resulting from the preservation of the main fraction; increase in the commodity fraction – additional income from increasing the share of grain suitable for sale. The data is calculated based on average production and market indicators
Source: developed by the authors based on data from Kernel (2025), Nibulon (2025), State Statistics Service of Ukraine (n.d.), MHP (n.d.)

The analysis of the data shown in Table 7 shows a significant economic effect achieved as a result of the introduction of optimised operating modes of the vibration cleaning machine. The greatest overall effect was recorded for millet – 81.2 UAH/tonne, which is explained not only by a significant reduction in losses, but also by a significant increase in the commodity fraction, which traditionally has a higher market value. Indicators for barley and wheat also indicate the profitability of technical changes, providing overall savings of 74.3 UAH/tonne and 66.8 UAH/tonne, respectively. It is worth emphasising that specific electricity costs decreased in the range of 12.4-15.8 UAH/tonne, which is a significant factor in the structure of the cost of processing. Thus, Table 7 confirmed the relationship between technical optimisation parameters and direct financial benefits for agricultural entities. Optimisation of the operation parameters of the vibration cleaning machine helped to establish a clear relationship between the kinematic characteristics of the equipment and the efficiency of cleaning grain material. It was established that wheat, barley, and millet are characterised by different sensitivity to changes in the frequency and amplitude of vibrations, and to the angle of inclination of the working plane. The highest cleaning rates were observed at a frequency of 11 Hz and an amplitude of 4.5-6 mm with an angle of inclination of 10-13°, which provided an optimal balance between the speed of mass movement and the separation of fractions according to aerodynamic properties. Especially significant changes were recorded for millet, where improved movement dynamics led to a decrease in re-mixing and an increase in product efficiency. An additional analytical unit devoted to the energy feasibility of implementing optimised modes demonstrated a reduction in specific electricity costs while maintaining or increasing the level of purification. The calculation results showed an increase in the efficiency in the range of 5-7% depending on the crop, and a reduction in energy consumption to 1.9 W·h/kg in the case of millet. A direct relationship was recorded between the stability of the purification mode (determined by the coefficient of variation) and economic efficiency, which was manifested in an increase in the share of the commodity fraction. This dependence confirmed the validity of the technological model based on a combination of several motion parameters.

Testing of new modes in production conditions confirmed the possibility of their implementation in serial production lines without reducing overall productivity. Comparative analysis showed a decrease in seed loss to 0.8% and an increase in efficiency to 98.2% on average for all crops. Under the conditions of standard tariffs and processing volumes, the overall economic effect was obtained in the range of 66.8-81.2 UAH/tonne, which indicates the feasibility of large-scale implementation. Based on the results of the study, it is recommended: to use the frequency of 11 Hz as the base for vibration cleaning, to adapt the amplitude within 4.5-6 mm depending on the crop, to set the angle of inclination of the screen in the range of 10-13°, and to introduce modular adjustment of parameters depending on the morphophysical characteristics of the grain material. Consideration of the specifics of the regional agricultural infrastructure regarded these recommendations as adapted to practical implementation in the conditions of medium-sized enterprises in Ukraine.

Discussion

Optimisation of the frequency-amplitude characteristics of the vibration effect helped to quantify stable relationships between the parameters of the oscillatory mode and the efficiency of cleaning seed material, which turned out to be critical for improving the quality of agricultural products. The implementation of optimal modes contributed not only to reducing losses and increasing the selectivity of separation, but also to reducing specific energy costs, which corresponds to the principles of energy efficiency. The formalised relationships between the frequency, amplitude and quality indicators of purification allowed forming reasonable technological recommendations for adapting vibration modes to the morphophysical properties of grain, and to determine the potential for scaling parameters in high-performance systems.

The significance of the established dependencies was consistent with the provisions presented in the study by Z. Zhao *et al.* (2022), where the feasibility of optimising the vibration effect on seed material in corn purification processes was proved. The results of this study confirmed the importance of achieving stable particle excitation to ensure efficient separation of flow components, which is consistent with the recorded dynamic differentiation effect in this study. The established resonant correspondence of the parameters had a similar interpretation in their experimental model, which confirmed the consistency of the observed phenomena. Similar conclusions were obtained in the paper by D. Xiong *et al.* (2021), where the efficiency of a combined pneumatic-mechanical dispenser capable of compensating for seed supply instability using controlled vibration pulses was analysed. The results of this study focused on the importance of the parameters of the oscillatory effect for stabilising grain mass flows, which correlated with the identified features of the transportation mode in the machine under study. In addition, the expediency of regulating the oscillation parameters considering the granulometric composition of the mixture confirmed the relevance of the proposed multi-factor approach to optimising the cleaning process.

The study analysed the efficiency of implementing vibration excitation in purification processes, which helped to establish a close relationship between the stability of the vibration mode and the effectiveness of separation. Matching the vibration parameters with the physical and mechanical properties of the material provided a resonant correspondence, according to which the intensification of impurity separation occurred. Similar conclusions were presented in the study by J. Zhou *et al.* (2022), where effective excitation during the ginkgo harvesting process was provided by adjusting the frequency and strength of the vibration according to the characteristics of the object. The dynamic consistency of the parameters revealed in the framework of the performed study confirmed the relevance of the chosen approach, in particular, when achieving stable purification under resonant influence conditions. During the implementation of the study, the influence of the dynamic balance of the drive on the efficiency of seed transportation and the effectiveness of its separation was also confirmed. Determining the optimal eccentricity and stable vibration mode ensured the uniformity of the load on the screen surface and reduced material losses. According to the conclusions given by C. Popa *et al.* (2021), even minor deviations in the configuration of the drive mechanism led to a decrease in the quality of cleaning, which is fully consistent with the relationships found in the study between dynamic unbalance and a decrease in the uniformity of separation.

During experimental tests, instability of the movement of seed material was recorded when the direction of vibrations changes, which required clarification of the conditions for spatial movement of particles. Analysis of the dynamics of mini-tuber transport performed by Q. Niu *et al.* (2025), demonstrated the presence of amplitude-frequency fluctuations affecting the stability of the material feed in the vibrating feeder. These conclusions were directly confirmed in the results of the study, where similar violations were recorded in the case of deviations from the optimal oscillation mode, which led to a complication of the purification process. An important aspect of empirical verification of the efficiency of the system was the assessment of the process of filling bounded cells under variable conditions of spatial interaction of particles. Y. Cai *et al.* (2022) presented a multi-factor model that considered the limitation of the working volume of metering elements and the dynamic interaction of particles during seeding. The generalised conclusions coincided with the results obtained in the course of the study, which established a relationship between the cleaning efficiency, the degree of filling, and the characteristics of the vibration mode, which determined the feasibility of considering the volume-spatial parameters in the design of vibration cleaning systems.

As part of the study, it was found that the lack of coordination between the frequency of vibrations and the inertial characteristics of the system leads to an increase in specific energy consumption. This aspect was confirmed by the analytical conclusions of K. Tang *et al*. (2022), which summarised approaches to adaptive regulation of energy consumption in systems with vibrational components on the example of bioreactor processes. The presented recommendations for multiparametric optimisation of vibration effects aimed at reducing power consumption were consistent with the recorded results, where dynamic inconsistency led to overspending and reduced technological efficiency. Analysis of energy consumption dynamics confirmed that the use of adaptive mechanisms for controlling oscillation parameters allows achieving a balance between technological efficiency and energy saving. F. Matsunaga *et al*. (2022) substantiated the use of cyberphysical systems to optimise energy consumption in intelligent manufacturing. The approaches to adaptive control of technical modes proposed by the authors helped to reduce energy consumption without reducing productivity, which was consistent with the conclusions of the study, where the adjustment of vibration parameters in accordance with the properties of seed material provided rational energy consumption with stable cleaning quality.

As an experimental part of the study, the expediency of adjusting the oscillation frequency and geometric characteristics of working units to reduce specific energy costs was established. Confirmation of the effectiveness of such approaches was contained in the paper by S. Sivakumar *et al*. (2024), which present a model for energy optimisation in Industry 4.0 sensor node systems, based on the principle of balancing functional performance and minimising power consumption. The relationship between the technical parameters of the vibration mode and energy efficiency revealed in the study corresponded to the modelling logic implemented in the mentioned source. The results of the study confirmed that the lack of regulation of the oscillatory mode leads to irrational energy use and a decrease in the stability of operation under prolonged load. Similar patterns were described in the paper by D.J. Sun *et al*. (2021), where modelling of energy consumption by electric vehicles under variable urban load conditions was carried out. It was proved that only optimisation of technical parameters allows ensuring economic efficiency without loss of operational reliability, which was consistent with the conclusions of the study on the importance of regulating the vibration effect against the background of variable mass and density of seed flow.

One of the significant factors affecting the level of separation was the contact relationship between the grain material and the elements of the vibration cleaning unit. The study by M. Sohail *et al*. (2022) analysed the prospects for introducing seed coating technologies as a means of improving their interaction with technical systems. It was found that surface modification helps to reduce the friction resistance and reduce the probability of sticking together, which corresponded to the results of the study, in which the stabilisation of the movement of fine seeds was noted when using the adapted geometry of working elements. The analysis of the aerodynamic support of the cleaning process showed the need for a comprehensive approach to regulating air and oscillatory effects. The study by J. Wang *et al*. (2021) demonstrated the effectiveness of an internal filling pneumatic mechanism for precise seeding, in which the consistency of air flow with design parameters determined the effectiveness of operation. Similar patterns were established in the study: a change in the force of the air flow in the vibration-aspiration unit caused variability in the quality of cleaning, which required simultaneous adjustment of the fan power and vibration parameters to achieve a stable mode. As part of the study, special attention was paid to the influence of the biophysical characteristics of seed material on the constancy and uniformity of its transportation in the working chamber. As evidenced by K. Zhang *et al*. (2022), the use of a BioCarbon coating has contributed to improving the dynamic properties of grain, reducing energy losses during movement, and improving processing efficiency. A similar trend was recorded in the implemented experiment, where grain particles with a uniform surface structure showed a more stable trajectory of movement. This ensured a uniform load on the screen surface and reduced the risk of undivided fractions forming. Similar patterns correlated with the findings of H. Tang *et al*. (2022), which presented an optimised design of a precision metering device with a long belt gripper, which guarantees uniform feeding of corn seeds and stable operation under various conditions. The researchers also emphasised the effectiveness of the built-in monitoring system, which helped to adjust the seed supply in real time, improving the accuracy and uniformity of dosing.

Improving the functional properties of the vibration system through digital technologies was analysed in the context of improving the stability of cleaning processes. As demonstrated by R. Reddy (2022), the use of innovative solutions in the field of precision farming provides a significant reduction in the impact of the human factor on the accuracy of equipment tuning. The results obtained as part of the study confirmed that the integration of sensor systems and frequency regulators helps to stabilise the separation parameters under conditions of variable impurity composition. Combined with this, W. Ma *et al*. (2023) proved that the use of adaptive technology in agricultural production allows achieving increased environmental efficiency due to optimal adjustment of technical parameters. Thus, the results of the experiment confirmed that the reduction of energy consumption and emissions is possible if the correspondence between the oscillatory regime and the characteristics of the grain mass is ensured. The problem of losses in the post-harvest period has become particularly relevant in the context of improving primary cleaning. A critical review by B.J. Olorunfemi & S.E. Kayode (2022) found that a significant proportion of losses are caused by high levels of residual humidity and insufficient efficiency of primary cleaning mechanisms. The empirical data obtained as part of the study indicated a decrease in the volume of fine impurities after the first separation cycle, which potentially minimises the need for re-cleaning and reduces storage losses. An additional perspective in this context is opened up by works on the relationship between the parameters of purification and the quality of grain preservation, which requires further research based on the results obtained.

In the study, modelling of the dynamics of seed movement was implemented on the basis of a discrete element method, which made it possible to track the trajectories of particle movement and form an adaptive oscillation profile. The feasibility of this approach was consistent with the conclusions of D. Yan *et al*. (2022), who demonstrated the effectiveness of using the discrete element method to predict the behaviour of soybean particles in agricultural systems. Similar provisions are reflected in the study by L. Wang *et al*. (2021), which described the introduction of a bioinspired oscillation principle based on the movement of earthworms. Both approaches confirmed that the adaptation of structural elements of vibration cleaning equipment to the physical characteristics of grain is a key prerequisite for ensuring uniform feed and reducing stagnant zones in the working chamber. The study also confirmed the possibility of reducing post-harvest losses by improving the efficiency of primary cleaning. In particular, E.E. Tiguh *et al*. (2024) proved that insufficient purification at the initial stages of teff processing is one of the main reasons for the loss of quality and volume of finished products. This logic was confirmed by the results of the experiment, where improving the screen geometry and adjusting the oscillatory mode helped to minimise the amount of impurities without the need for a second cleaning cycle. Thus, the results obtained not only confirmed the relevance of modern approaches to engineering modelling, but also allowed proposing optimisation solutions adapted to different types of seed material.

Generalisation of the results showed that the research corresponds to current scientific and applied areas in agricultural engineering. The ratio between the frequency-amplitude parameters of vibration exposure, the characteristics of grain mass and the dynamics of its transportation allowed formulating basic technical and technological provisions for the design of new-generation cleaning systems. The synergistic combination of digital, biophysical and engineering components provided a comprehensive effect of stabilising the workflow while reducing energy consumption. Thus, the results of the study can be used for further modernisation of vibration technologies in the agro-industrial sector, considering the principles of energy efficiency, technological adaptability, and functional reliability.

Conclusions

As part of the study, a differentiated method for optimising the kinematic parameters of the oscillatory mode for cleaning wheat, barley, and millet seeds was developed and tested. Based on multivariate analysis, it was found that the frequency of 11 Hz, the amplitude of 4.5-6 millimetres and the angle of inclination of 10-13 degrees are optimal for ensuring high quality of cleaning without exceeding the permissible grain losses. For each crop, clear parameters were set that allowed achieving a cleaning efficiency of 98.2% for wheat, 97.3% for barley, and 98.4% for millet with a loss of the main seed not exceeding 1.3%. The results of the energy analysis confirmed the effectiveness of the optimised modes. Specific electricity consumption for wheat was reduced to 0.92 W·h/kg, for barley – to 1.05 W·h/kg, for millet – to 0.88 W·h/kg, which was accompanied by an increase in efficiency to 87-89%. According to the results of testing in real production conditions, the decrease in specific losses reached 0.7-0.9%, while the increase in the commodity fraction was 1.6-2.5%. In monetary terms, the overall effect of implementing optimised regimes ranged from UAH 66.8 to UAH 81.2 per tonne of purified material, which confirmed the economic feasibility of the recommendations. Additionally, it was found that the coefficients of variation of the cleaning quality did not exceed 3.3%, which showed the stability of the process with repeated modes.

The key advantage of the developed methodology was the combination of analytical assessment of grain mass movement with validation through field tests. It was established that a crop-specific approach to tuning the frequency-amplitude mode allows adapting equipment to specific characteristics of raw materials without changing the design of machines. The obtained data allow formalising the approach to the rules for setting up vibration cleaning equipment, considering the target indicators of cleaning efficiency of more than 97%, losses of less than 1.5%, unit costs of no more than 1.1 W·h/kg. It is recommended to introduce optimised frequency-amplitude modes in production with preliminary adaptation to the physical properties of a particular batch of seeds. Promising areas of further research are the development of an automated system for regulating the vibration mode with sensory diagnostics of grain mass movement, and the analysis of the influence of sieve structures and guide elements on the efficiency of breeding small organic impurities. It is also advisable to investigate the long-term effects of optimised modes, considering the wear of machine elements, and develop an integral criterion for energy-quality efficiency for comparing cross-cultural settings.

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Conflict of Interest

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Оптимізація робочих параметрів віброочистної машини для підвищення якості очищення насіння

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Анотація. Актуальність дослідження зумовлювалася необхідністю підвищення ефективності очищення зернового матеріалу в умовах енергообмежених агропереробних підприємств України. Метою дослідження було визначення оптимальних кінематичних параметрів вібраційного режиму роботи машини з урахуванням специфіки очищення насіння пшениці, ячменю та проса. Для досягнення поставленої мети було проведено серію експериментальних досліджень із використанням високошвидкісного відеозапису, цифрової обробки зображень, дисперсійного аналізу та енергоаудиту. У результаті встановлено, що оптимальні параметри вібраційного режиму – частота 11 герц, амплітуда 4,5-6,0 міліметрів та кут нахилу 10-13 градусів – забезпечували найвищі показники ефективності очищення для трьох культур. За цих умов досягнуто середнього рівня ефективності очищення на рівні 98,2 % для пшениці, 97,3 % для ячменю та 98,4 % для проса, при зниженні питомих втрат насіння до 1,2 %, 1,3 % та 0,9 % відповідно. Одночасно зафіксовано зменшення залишкових домішок до 0,6-1,7 %, стабілізацію технологічного процесу (коефіцієнт варіації не перевищував 3,3%) та підвищення коефіцієнта корисної дії до 87-89 %. Питомі витрати електроенергії зменшилися до 0,88-1,05 ват-години на кілограм, що зумовило економію на рівні 12,4-15,8 гривень на тонну очищеного матеріалу. Загальний економічний ефект за рахунок сукупного впливу на енерговитрати, втрати насіння та приріст товарної фракції склав 66,8-81,2 гривень на тонну, що підтвердило практичну ефективність застосування нових параметрів в умовах серійного очищення зерна. Отримані результати можуть бути використані інженерами, технологами та проєктувальниками для оптимізації режимів функціонування віброочистних систем у зернопереробній галузі

Ключові слова: енерговитрати; коефіцієнт корисної дії; рівномірність навантаження; коливальний режим; економічний ефект; амплітуда коливань