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QUANTITATIVE ASSESSMENT OF WHEAT MECHANICAL INJURY DURING FREE FALL IN TRANSPORT AND PROCESSING LINES

The object of research is the process of gravitational fall of grain during its movement along a typical transport and technological line at the enterprise. The problem of the lack of a comprehensive analysis of operational deficiencies of transport equipment, which leads to mechanical damage to grain, was solved. The results of a comprehensive research of the impact of free fall of grain from different heights on surfaces with different physical and mechanical properties are presented. The relevance of the work is due to the need to minimize post-harvest losses of grain, which due to equipment imperfections can reach 55–65% of the total volume.

The nonlinear nature of the change in the speed of grain fall under gravity was experimentally established: on a section of up to 10 m, the speed increases to 12.4 m/s, after which it stabilizes within 13.3 m/s under the influence of air resistance. It is proven that the type of material of the surface in contact with the grain is a determining factor in the intensity of damage. The highest injury rates (up to 0.6%) were recorded in contact with Hardox 450 steel, while the use of polyurethane lining reduces the level of damage by 12%. The most trauma-saving method was recognized as the "grain on grain" method, which provides a reduction in injury by 54–57%. A direct correlation was established between the angle of inclination of the surface and the degree of destruction of the kernel: a direct impact (90°) is critical, which increases the level of macrotrauma by 2–2.4 times. Using the method of staining with aniline dyes, a hierarchy of vulnerability of the grain structure was identified, where endosperm microtrauma occurs in any fall regime. This difference in injury can be explained by the ability of materials to absorb kinetic impact energy. The appearance of endosperm microtrauma in any regime indicates the fragile nature of the starch structure of the kernel.

Scientifically based recommendations are provided on limiting the height of free fall to 4 meters and introducing grain gravity-braking devices to preserve grain quality.

Keywords: mechanical injury to grain, influence of free fall, speed of wheat flight, experiment, angle of impact.

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1. Introduction

The main task of the agro-industrial complex of Ukraine is to organize and stably provide the population with high-quality food products. Grain is an important strategic resource that forms the food security of Ukraine and is a valuable raw material for the production of a large number of food products. Damage and injury to grain caused mechanically during movement along transport and technological lines (TTL) is one of the reasons for the deterioration of its quality both during storage and for a further decrease in the level of germination and growth strength of seed material. Depending on weather and climatic conditions, soil, biological, varietal and mechanical and technological features, grain damage can reach 55–65% of the total volume [1]. Ensuring high quality grain at all stages from harvesting to shipment to the end consumer is a key factor in Ukraine's competitiveness in international markets. Therefore, increasing yield for producers is an urgent task today. The basis of high yield of agricultural crops is high-quality seed material.

One of the main sources of losses is grain injury caused mechanically during its movement in transport equipment – elevators, conveyors, augers and gravity pipes. Each stage of grain movement leads to the collision and friction of grains between the working parts of the equipment and among themselves. Moisture and air penetrate into

microcracks and fractures, which has a negative effect on the shelf life of the grain. When storing such grain, segregation increases, which also affects the safety and shelf life of the product. Segregation occurs when the container is loaded with a compact flow by gravity. At the same time, the grain actively breathes due to free access of air to the internal structure of the grain, its temperature increases, self-heating occurs, fungal diseases and microorganisms spread. In the grain mass, with free access of oxygen, two thermal processes occur simultaneously in different areas: heat transfer and its release. The ratio of the number of these processes determines the rate of temperature propagation, the depth of penetration of the thermal zone, the rate of temperature change and heat flow in different parts of the grain mass. In general, the grain layer is characterized by low thermal conductivity, which can be equated to the thermal conductivity of high-quality thermal insulation materials. But damage to the grain leads to such a phenomenon as self-heating. This leads to a decrease in the commodity value of the grain, the sowing quality of the seed material deteriorates, which also leads to significant economic losses. The relevance of the problem is determined by its direct impact on the economic efficiency of the industry. Damage during technological processes can reach 55–65% [1]. Economic losses are complex in nature [2] and consist of direct losses in the reduction of grain mass, a decrease in price due to a deterioration in grain quality,

an increase in storage costs, as well as reputational losses for Ukraine in international markets. Destruction also changes the physicochemical properties of the grain, which affects the final quality of the product [3].

The relevance of research is due to the need to solve the critical problem of significant losses and deterioration of grain quality during its transportation by TTL. When conducting a comprehensive research dedicated to studying the impact of TTL grain movement on its damage, a significant gap in research was identified. While the existing literature thoroughly examines the overall post-harvest losses of grain and various storage and transportation methods, there is a noticeable lack of in-depth analysis specifically focused on the operational shortcomings of equipment in agricultural processes. This gap is critical because it does not comprehensively take into account the mechanisms that contribute to grain damage during the movement of TTL material, which can significantly affect the overall quality of the grain and future yield. Addressing this gap is important for the development of more efficient and less harmful methods of working with grain, thereby increasing agricultural productivity and reducing post-harvest losses in the agro-industrial sector.

Increasing the level of consumer and marketable properties of grain material requires manufacturers of transport and technological equipment to use innovative technologies in its production. Although reducing the force interaction between the grain and the working body of the equipment is one of the indicators of the high technological level of the manufacturer, most of the attention is still directed to increasing the level of mechanization, increasing the productivity of equipment, increasing the reliability of equipment and reducing operating costs. The effectiveness of using existing means that affect the nature of grain damage remains very low. At the same time, there are no production, laboratory and experimental studies of grain microtrauma in technological processes of grain processing, with the exception of several TTL elements [4]. The scientific substantiation of theoretical and experimental data on grain injury research in agricultural engineering is quite limited. Most researchers define the scope of their research only by quantitative assessment of damage, and only a few have conducted in-depth studies of individual nodes to understand the mechanisms of grain damage. Therefore, conducting comprehensive research at all stages of technological processes of grain transportation is an urgent scientific problem. A significant number of studies are related to the processes of loading silos. Studies of Poltava State Agrarian University investigate this process in detail. In paper [5], the frequency of grain impact during their gravitational movement in the grain medium was investigated. Research [6] considers the oblique impact of grain on the concrete bottom of the silo as a result of its free fall. In paper [7], the main characteristics of the impact interaction of grain with a stationary obstacle, namely the bottom of the silo, are determined. A dependence was obtained for determining the impact force of grain and it was established that its magnitude depends on the speed of movement and the height of fall, as well as on the physical and mechanical properties of the bottom of the silo. An analytical model of grain movement [8] was developed and based on it, a device with discretely variable angles of inclination of the acceleration and deceleration chutes [9] was proposed. The optimal angles of inclination of the chutes and their dependence on the angle of natural slope were established. An experimental gravity cascade installation [10] was developed for controlled vertical movement of grain with a decrease in its speed due to braking and acceleration sections. The ratio of the inclination angles of the acceleration and deceleration shelves of the device was found and the values of the recommended angles were substantiated. The study [11] considers a laboratory installation in the form of a torus-shaped plate, onto which grain first falls, and from which it is then poured onto the concrete bottom of the silo. The dependence of grain distribution on the height of grain discharge and the angle of inclination of the forming plate to the horizon was established. Thus, the best distribution occurs at an angle of inclination of 12°, but the height of grain fall should exceed 1.5 m.

No less significant research has been conducted on bucket elevators. In [12], the forces that arise during the operation of the elevator, the parameters of the elevator operation: drive power, belt speed, the use of a variable-speed elevator by using a grooved stepped pulley in the drum drive is proposed. Paper [13] describes self-supporting high-performance elevators, options for drum drives. The advantages and disadvantages of existing design plans are considered, and means for the effective use of equipment are proposed. In [14], the authors study and evaluate the factors that affect grain injury during its lifting and unloading. The arrangement of several structures to prevent grain damage is proposed, namely, rubberized plates in the lower part of the elevator boxes, adjusting the contours of the elevator head in accordance with the operating modes of the equipment, as well as installing mechanical, electronic or hydraulic dispensers in the upper unloading zone. The study [15] is aimed at increasing the productivity of grain elevators while ensuring the stability of filling the buckets by substantiating the structural and kinematic parameters taking into account the physical and mechanical properties of grain materials. The author concludes that all grain materials with a moisture content of $W < 12.5\%$ must be loaded into the buckets in the direction of the elevator operation. Wheat with an optimal moisture content of 14.5% and above can be loaded against the direction of travel. Corn grain has a more elastic and fragile shell and a soft endosperm, so its susceptibility to injury is very high. Even with an optimal corn moisture content of 14%, loading must be carried out in the direction of travel. In addition, the elevator operation should occur at speeds of 0.7–1.2 m/s for dry grain ($W < 12\%$) and 1.2–2 m/s for grain with a moisture content of 14% and above. Paper [16] is related to the calculations of the bucket at the time of scooping grain and its vertical transportation. Calculations of the strength, rigidity of the bucket and analysis of its operation depending on the wall thickness were performed. The optimal material and shape of the bucket were proposed [17]. In [1], the design parameters of the working elements of the elevator are also considered, the material from which they are made or covered, the angles of inclination and the step of placing the buckets. The author concludes that the injury of grains depends on the filling of the bucket, the speed of the belt, the surface area of the working element and on the reverse pouring of grain from the bucket. It has been experimentally proven that after the passage of rye seeds through the elevator, the amount of damaged grain increased by 3.7%. Research [18] analyzes the degree of damage by analytical methods. The concept of "conditional technical means" is introduced, for which the NZ-5 elevator is taken. Further studies are based on comparing the number of grain passages through transport lines and comparing the number of damages. Such an assessment system allows for a short period of time to determine the damage to the grain material without removing it from the technological process. A significant number of studies are related to the grain separation process. In [19], a structural model of the grain damage process during the separation process was created, regression equations were obtained that allow assessing the level of damage depending on the influencing factors. Dependence suitable for predicting microtrauma and grain damage was obtained. Paper [20] is related to the experimental study of grain movement along the gravity guide curve of the feeding device to establish the optimal characteristics of grain movement to the separator. In [21], a review of structures and analysis of the operation of sieve surfaces was conducted, the best conditions for the orientation of holes were established, and a new material for the manufacture of sieves was proposed. The author of paper [22] analyzes the movement of grain mixture particles in the chamber of a gravity-air separator during the action of an air flow of variable speed, outlines the real possibility of controlling the process of separating grain material components by aerodynamic properties. The paper [23] considers the operation of a conveyor with a screw working body. The analysis of the degree of grain injury using multifactor experiment planning methods was carried out. It was established that the main factor leading to an

increase in injury is the frequency of rotation of the working body. The study shows that the destruction of seed material due to impact interaction with the working surface of the screw can be reduced by reducing the angle of inclination of the screw, the angular speed of rotation of the screw and its radius. In this case, to reduce seed injury, it is advisable to use screws with a large pitch and polymer screws with a wider pitch.

Despite such a large number of researches, none of them took into account the simultaneous number of factors related to the height and speed of the gravitational fall of the grain, the material of the impact surface and the angle of its inclination to the movement of the grain. And at the same time, the movement occurs in a typical grain gravity. There is no deep and comprehensive analysis of operational deficiencies of the equipment that lead to mechanical damage to the grain during its movement by TTL.

One of the causes of damage to the grain during its movement by TTL is free fall. During transportation operations, depending on their nature, the seeds can fall from different heights and hit different surfaces, receiving shock loads that cause deterioration in quality. Depending on the type of operation, the grain can fall both from several meters in gravity, and from heights of more than 30 m when loaded into a bunker or silo on elevators.

The object of this research is the process of gravitational fall of grain during its movement by a typical TTL at the enterprise.

The aim of this research is to quantitatively assess the damage to wheat seeds during free fall in gravity under the influence of gravitational forces during a change in the direction of its movement due to contact with a guiding surface.

To achieve the aim, it is necessary to perform the following objectives:

1. To determine the speed of falling grain in gravity and its dependence on the height of fall.
2. To determine the dependence of grain damage on the height of fall when it hits different types of surfaces, materials and the angle of inclination of the contact surface.
3. To conduct an analysis of the vulnerability of structural elements of the grain using the direct staining method.

2. Materials and Methods

2.1. Samples and their preparation

As is known, the outer surface of the grain is protected by a fruit shell, which consists of several layers. Behind it is a seed shell, which also has several layers. Both of these shells protect the grain from external negative influences. During grain ripening, the biological and chemical composition of both the shell and the entire grain changes significantly. When the amount of moisture decreases, the density increases sharply. The surface can be smooth, bumpy, glossy, wrinkled or ribbed, which is formed not only by varietal characteristics, but also by external factors: water, sun, soil and its fertilization. The location of the grain in the ear also affects the quality. Thus, the largest size is the grain located in the middle of the ear, while up and down from the middle there is a decrease in the size, quality and germination of the grain. For the research, the soft wheat variety Yulia (originator – Selgen) was taken, in which the embryo is not completely covered by the shell. As a result, the soft wheat grain has less strength compared to hard varieties, in which the embryo is completely covered. Intact seeds were obtained by manual collection in the Podilskyi district of the Odessa region at the optimal stage of ripening. In order to avoid damage, all work on sample preparation was carried out manually: collecting spikelets, threshing them, cleaning them to basic garbage impurities. Storage before the start of the experiment took place in a dry, ventilated room. Before the experiment, the initial humidity was determined. 80 samples weighing 300 ± 0.1 g each were formed. The experimental equipment included:

- electronic scales for packing samples before the start of the experiment TVE-3-0.05 (accuracy $d = 0.1$ g) ("Technovag" LTD,

Ukraine) and FEN-300 (accuracy $d = 0.01$ g) ("Dneproves" LTD, Ukraine) for weighing after the experiment;

- digital video camera SM-S911B/DS (SAMSUNG, Vietnam);
- optical magnifying glass 10-fold (BUROMAX, Ukraine);
- laboratory drying cabinet MO212 ("Technotest" PE, Ukraine) for determining humidity.

Table 1 describes the physical and mechanical properties of the wheat sample under study, as well as the standards that were used in the work.

Table 1

Values of physical and mechanical properties of the sample

Name	Indicator value	Research standard
Moisture w , %	13.7	ASAE/ASABE D241.4 (R2022)
Native weight γ , g/dm ³	787	ISO 7971-3
Weight of 1000 grains M , g	49.56	DSTU EN ISO 520:2022
Grind vitreousness, %	47	ISO 7970:2021
Waste impurity, %	1.5	ISO 7970:2021
Grain impurity, %	0	ISO 7970:2021

2.2. Gravity drop test

The conditions of free fall in the air environment were simulated in the production conditions of an operating enterprise in order to assess the impact of free fall of wheat samples onto different surfaces at different angles of inclination from different heights on the degree of damage to the grains. The node in which the direction of grain movement changes is considered: at the grain inlet to the conveyor. An experimental installation was made, which was based on a metal pipe with a circular cross-section and a diameter of 300 mm. The height from which the grain was dropped was 2, 4, 6, 10 and 16 m. A round pipeline is quite often used in production as gravity transport equipment. It is more common compared to rectangular [24]. The length of one section of 2 m is also the most common among equipment manufacturers.

The surfaces used for contact with the grain flow are common in the production of grain transportation equipment:

- Hardox 450 sheet steel 4 mm thick;
- PE 1000 high molecular weight polyethylene sheet 10 mm thick;
- steel sheet lined with "ELASTOMER PZU 2319" polyurethane 6 mm thick;
- wheat grain layer 50 mm thick.

The hardness of the materials used, declared by the manufacturers, is summarized in Table 2.

Table 2

Hardness values of the contact surface

Name	Hardness value	Research standard
Hardox 450 steel	425–475 HBW	EN ISO 6506-1
PE 1000 high molecular weight polyethylene	60, scale D	ISO 868-85
"ELASTOMER PZU 2319" polyurethane	85-87, scale A	ISO 868-85

The surface of the wheat grain layer was covered with a very thin polyethylene film, which held the grain and prevented it from mixing with the samples. The film was in constant contact with the grain surface. Each surface had a size of approximately 50×50 cm and was inclined at an angle of 30° , 45° , 60° i 90° to the horizon. Each seed sample was dropped from a predetermined height. Thus, a total of 80 experiments were conducted. Grain temperature $+19^\circ\text{C}$. Ambient temperature $+20^\circ\text{C}$. Grain feed rate was 0.3 kg/s. To facilitate the collection of test samples, polyethylene film was used, which was spread on the surface. The experimental unit is shown in Fig. 1.

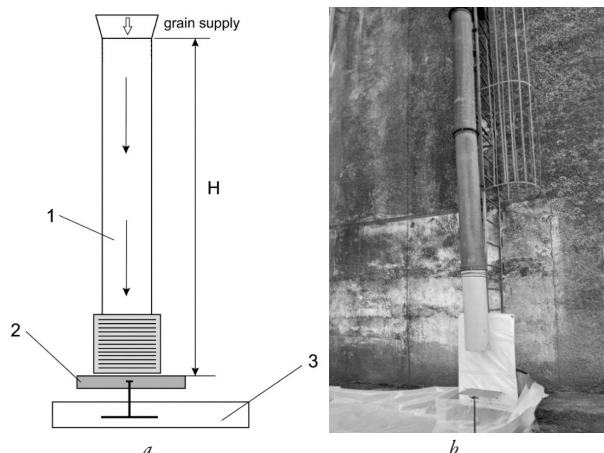


Fig. 1. Experimental unit used in the free fall experiment: *a* – diagram; *b* – general view; 1 – pipe with a diameter of 300 mm, 2 – contact surface; 3 – grain collection container

2.3. Measurement of grain velocity

The velocity of grains was measured by dropping them into gravity and video recording in the flow of movement at the exit of the pipe. Between the lower end of the pipeline and the contact surface at an angle of 90°, a distance of approximately 0.6 to 0.7 m was maintained to record the speed of grain exit from the pipe. In the background, for the convenience of observing the distance traveled by the seeds, a special drawing paper was installed, marked with an interval of 1 mm to facilitate accurate measurement of the distance traveled. Video recording of the grain flow was made to determine the speed of grain movement, which depends on the height of the fall and air resistance. Since tracking each individual grain in the mass flow was difficult, the grain speed was recorded at the beginning and end of the mass flow. The registration was carried out using a digital camera.

2.4. Inspection and analysis of damage

As is known, all methods of research into grain injury can be divided into two groups:

- direct – this is the direct detection of cracks and damage by inspection through various technical devices (magnifying glass, diaphanoscope, X-ray or tomograph);
- indirect – determination of indicators that correlate with injuries or similarity, including treatment with chemicals [25].

One of the modern direct methods is the method of intelligent detection of damaged grains based on machine vision using the ResNet model [26], which consists of the CBAM spatial observation module and memory blocks. RGB images of grains of different quality are recorded in the memory of the modules. Grain batches are inspected using this model. The recognition accuracy of ResNet was 97.5%.

The level of grain damage can also be investigated by X-ray computed microtomography [27]. This is also a non-destructive technology that provides visualization of samples in two dimensions (2D). The results obtained by X-ray computed microtomography are close to those obtained by microscopy. The obtained 2D X-ray images can be converted into 3D models using software.

Another modern method for determining quality is a deep machine learning algorithm as a direction of artificial intelligence that integrates data from four sources: hyperspectral imaging and computer vision, obtained from both the surface of the embryo and the surface of the endosperm [28]. These data are combined with scanning electron microscopy of the grain. This data fusion strategy is multifaceted and has significant prospects for practical application and can record such damages as mold, germination, internal damage by pests in cases where the external appearance of the grain is intact and cannot be distinguished by the naked eye. This model achieves a recognition accuracy of 94%.

Based on the analysis of all known direct and indirect methods, it is possible to choose the direct staining method [25]. The technique is based on obtaining different colors of seeds depending on the nature of its damage. The more damaged the grain, the more strongly the fracture site is stained. Different substances are used for this. Aniline dye was chosen in a solution concentration of 1%. The samples were kept in the solution for 2 min, after which they were washed and spread on filter paper for drying. The research was carried out in laboratory conditions by qualified laboratory technicians. After drying, each grain was examined through an optical magnifier with a tenfold magnification. Particular attention was paid to the embryo and endosperm. Then, sorting was carried out by type of injury and determining the nature of the damage. Sorting was carried out by the following groups:

- grain with endosperm microinjuries;
- grain with embryo microinjuries;
- grain with endosperm macroinjuries;
- grain with embryo macroinjuries;
- broken grain.

The last stage was weighing the damaged grains on a scale. The number of damaged grains in each group was determined by the formula

$$\Delta I = \frac{M_{dam}}{M_{tot}} \cdot 100\%, \quad (1)$$

where M_{dam} – the weight of damaged grains, g; M_{tot} – the weight of the total batch, g.

This method is most suitable for agricultural enterprises with an average number of mechanized processes and has sufficient accuracy to determine the degree of seed damage. It allows to visualize and study structural changes in the grain, such as damage to the shell, endosperm and embryo, the presence of cracks and changes in the color or texture of seed tissues, and also has a number of advantages over other methods. For example, this method does not require complex instruments or special conditions. It is a relatively quick and affordable procedure that can be performed using a conventional microscope or magnifying glass. This method is non-invasive, that is, it does not require the destruction or division of the seed into parts, which preserves the integrity of the seed for further use or additional research. Staining seeds and examining them through a magnifying glass is a relatively inexpensive method that does not require the use of expensive equipment or chemicals. This makes it available both in the laboratory and in production.

The task was to calculate the percentage of damaged seeds based on their weight relative to the total weight of the sample.

3. Results and Discussion

3.1. Determination of the velocity of gravitational fall of a grain in gravity flow and its dependence on height

The velocity of grain fall in a closed gravity flow was determined according to the experimental data obtained. The value of the velocity of grain fall and the dependence of the gravitational movement of grain on the fall height in a gravity flow with a diameter of 300 mm are shown in Fig. 2.

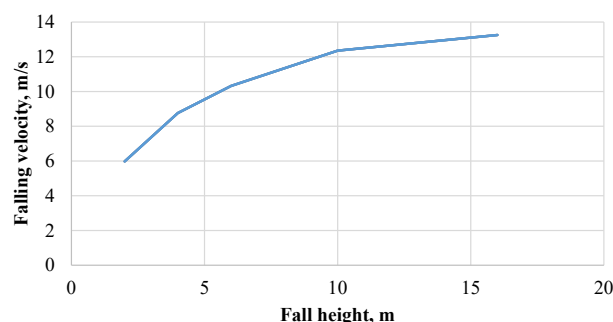


Fig. 2. Graph of grain velocity in air space dependence on drop height

3.2. Research of grain damage dependence on drop height, angle of inclination and surface material

The experiment was built in the form of a factorial design. The factors were the grain drop height with five levels and four contact surfaces with four levels each. A total of 80 (5 × 4 × 4) factors were determined. The factorial design helps to determine the independent influence of each factor, as well as to assess the joint effect of two or more factors simultaneously, i. e. to determine the interaction effect. In order to compare the values, elements of multiple comparison were used, namely Duncan's multi-range test (MRT).

When wheat seeds collided with a flat, even surface, some of the grains were injured.

At a drop height of 2 m, the proportion of injured seeds is expectedly small. The number of damaged grains when falling on a Hardox surface and a polypropylene surface does not differ and is 0.05–0.15%. The number of injured grains when falling on a polyurethane surface is 12–54% less, depending on the angle of inclination of the contact surface during the fall, and is 0.02–0.12%. The number of injured grains when falling on grain is generally insignificant – up to 0.04%, depending on the angle of fall.

When seeds fall from a height of 4 m, the highest rate of grain damage was recorded when falling on Hardox steel: 0.1–0.25%. Damage when falling on a polypropylene surface is also close to the data on the steel surface. The injury of seeds when falling on grain is 28–37% less, and is 0.02–0.14%.

When seeds fall from a height of 6 m, comparably higher results were obtained. The highest rate of grain damage was recorded when falling on Hardox steel: 0.12–0.36%. Lower rates were recorded when falling on polypropylene: 0.11–0.29%; polyurethane: 0.1–0.24%. The number of injured grains when falling on grain was 0.08–0.2%.

At a grain fall height of 10 m, the following results were obtained. Again, the highest rate of grain damage was recorded when falling on Hardox steel: 0.27–0.54%. Slightly lower rates were recorded when falling on polypropylene: 0.23–0.49%; polyurethane: 0.17–0.38%. When falling on grain, 0.13–0.3% of damaged grains were obtained.

And when seeds fell from a height of 16 m, correspondingly higher results were obtained. The highest number of injured grains was recorded when falling on Hardox steel: 0.28–0.6%. Lower numbers were recorded when falling on polypropylene: 0.23–0.56%; polyurethane: 0.2–0.47%. The lowest number of injured grains was recorded when falling on grain: 0.16–0.33%.

Fig. 3 shows graphs of the dependence of grain damage when it falls on Hardox 450 sheet steel, PE 1000 sheet polyethylene, a steel sheet lined with "ELASTOMER PZU 2319" polyurethane and a layer of wheat grain installed at angles of 30°, 45°, 60°, 90° from a height of 2, 4, 6, 10 and 16 m. When grain falls on the surface at an angle of 30°, the highest rates of grain damage were expected when falling on Hardox steel: 0.05–0.29%. Almost the same amount of damage was

recorded from falling on polypropylene: 0.05–0.24%. Falling on a polyurethane surface has similar values: 0.02–0.24%. The number of injured grains when falling on grain was 0.01–0.16%.

When seeds fell on the surface at an angle of 45°, slightly higher results were obtained. The highest damage rate was recorded when falling on Hardox steel: 0.08–0.4%. Similar rates were also obtained when falling on polypropylene: 0.07–0.4%; polyurethane: 0.1–0.28%. Damaged grains when falling on grain had 0.01–0.2%.

When grains hit the surface at an angle of 60°, the highest rates of grain damage were again obtained when falling on Hardox steel: 0.11–0.51%. Similar values were recorded from falling on a polypropylene surface: 0.11–0.44%. Lower values were obtained when falling on a polyurethane surface: 0.09–0.38%. And when falling on grain, 0.03–0.3% of injured grains were obtained.

The highest grain injury rates were obtained when seeds fell on the surface at an angle of 90°. So, when falling on Hardox steel: 0.15–0.6%. Close to these indicators – and from falling on polypropylene: 0.15–0.56%. Somewhat lower – when in contact with a polyurethane surface: 0.12–0.47%. Damaged seeds when falling on grain were obtained 0.04–0.33%.

The dependence of the percentage of grain injury on the material and the angle of inclination of the contact surface are shown in Fig. 4.

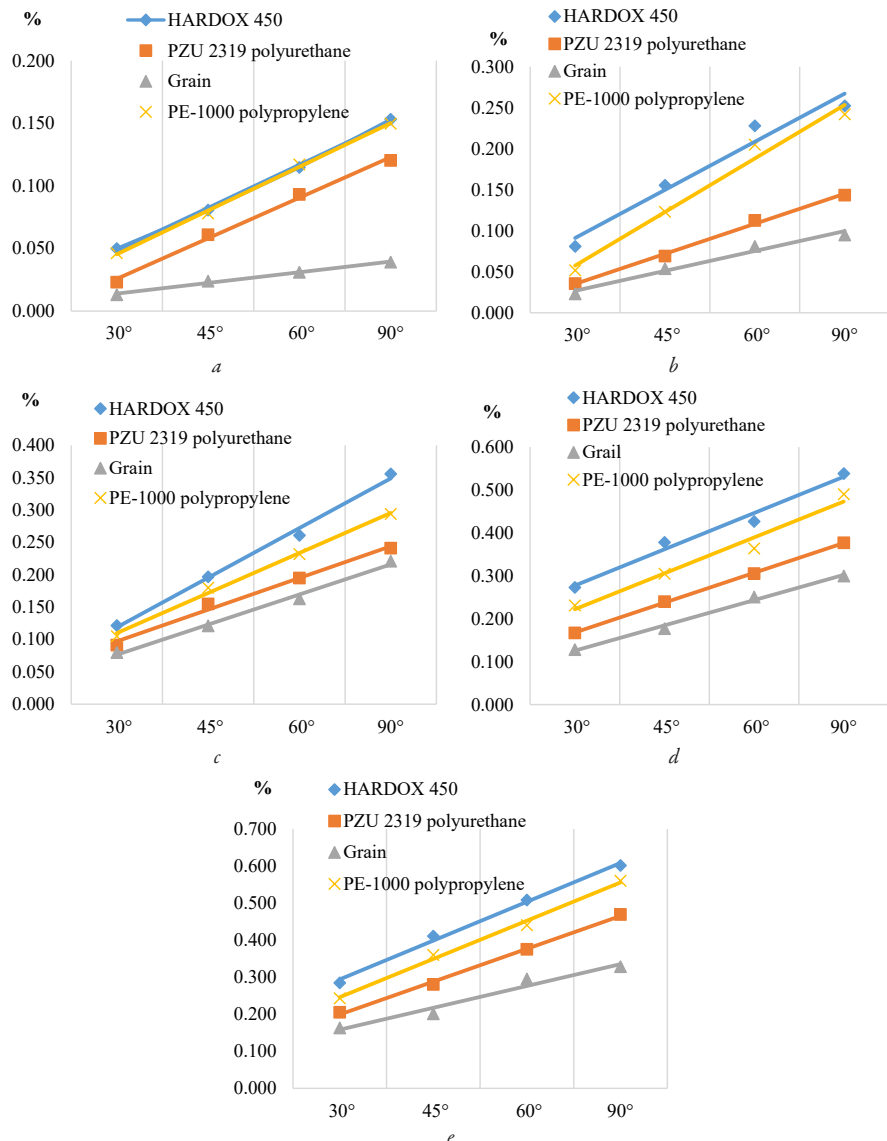


Fig. 3. Graph of grain damage dependence on the angle of fall on plates made of Hardox 450, PE 1000 polyethylene, "ELASTOMER PZU 2319" polyurethane and a layer of wheat grain from a height: a – 2 m; b – 4 m; c – 6 m; d – 10 m; e – 16 m

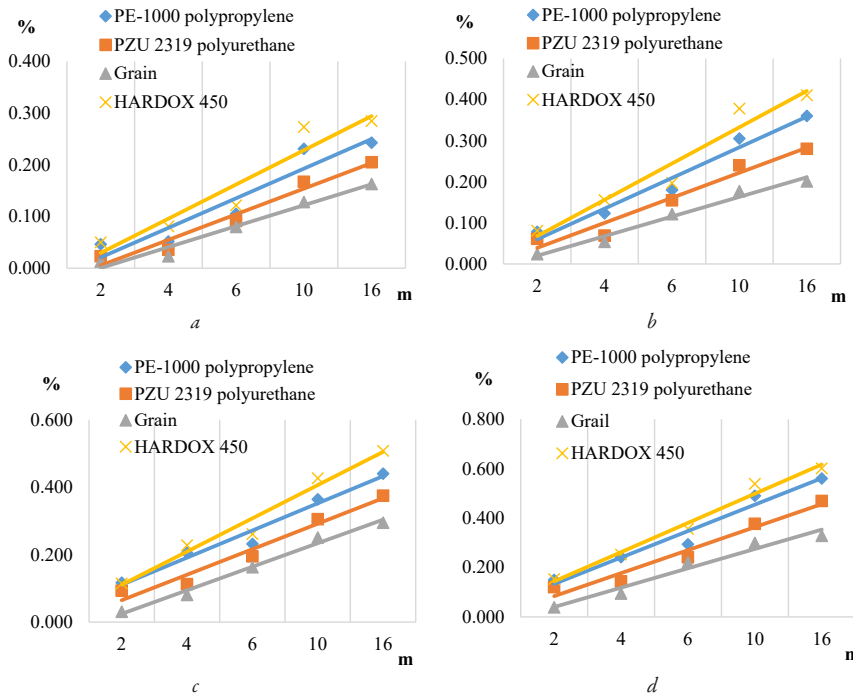


Fig. 4. Graph of grain damage as a function of height when it falls on plates made of Hardox 450, PE 1000 polyethylene, "ELASTOMER PZU 2319" polyurethane and a layer of wheat grain, which are installed at angles: a – 30°; b – 45°; c – 60°; d – 90°

Therefore, the choice of the contact surface significantly affects the damage to the grain. The largest number of injured seeds was obtained when it fell on a steel surface made of Hardox 450. When the grain fell on a polyethylene sheet, the number of injuries decreased by 6–14% depending on the angle of incidence of the grain. This difference is quite small, therefore, when manufacturing or modernizing transport equipment, the choice for the use of these materials may be due primarily to economic calculations and design features. Slightly better indicators were obtained when the grain came into contact with a polyurethane surface. Compared to impact on a polypropylene surface, the level of injury is reduced. For the research, a budget version of a 6 mm thick polyurethane coating of the PZU-2319 brand was taken, which is a fairly common option, with a Shore A hardness of 85-87. However, in the world there are different types of polyurethane coating with greater thickness, with reinforcement, with lower hardness. Accordingly, the indicators when using them can vary significantly. And the most effective was the fall of grain on grain. The number of injured grains in this case was 54–57% less than in contact with Hardox 450 and 15–30% compared to the polyurethane coating.

3.3. Analysis of the vulnerability of structural elements of the grain using the direct staining method

The use of the staining method with aniline dyes made it possible to visualize damage that usually remains invisible with a simple visual inspection. Since the dye penetrates only into the places of tissue rupture, the intensity of the grain color is a direct indicator of the depth of grain destruction. The most important result of the analysis was the detection of endosperm microtraumas in absolutely all experiments conducted, regardless of the height of the fall or the type of surface. This indicates that the internal starch structure of the soft wheat grain has an extremely low resistance to shock loads. Even with minimal collision energy, microcracks appear inside the endosperm. And although such damage does not change the geometric shape of the grain, it critically affects its quality. Microtraumas of the germ were determined in experiments up to a height of 10 m at an angle of inclination of 60° and 90° in an insignificant amount of 0.04–0.08%. At a fall height of 4 m, endosperm macrotraumas

already appear and the number of microtraumas of the germ increases. At the same height of the fall on Hardox 450 steel, broken grains were also recorded. Therefore, a height of 4 m is critical for preserving the integrity of the grain. A height of 16 m is catastrophically traumatic for seeds: significant microtraumas of the endosperm and embryo, macrotraumas of the endosperm, a large number of broken grains and up to 0.05% of macrotraumas of the embryo were obtained.

These results are of particular importance in the context of substantiating rational technical and technological solutions related to the design or modernization of TTL and aimed at reducing mechanical damage to grain in free fall conditions in gravity flows. The research results will supplement the information base on the implementation of trauma-saving technologies for grain transportation.

The limitations of the proposed research are the narrow range of ambient air and grain temperatures. In addition, the research was conducted in an open gravity flow, which may affect the speed of free fall of the grain flow. Another limitation is the research of wheat seeds, which, compared to other crops (corn, soybeans), is more resistant to injury.

In the future, it is planned to conduct comprehensive researches to establish the specifics of the impact of TTL sealing on the speed of free fall of grain, as well as to conduct similar studies on other grain crops.

3.4. Discussion

The data obtained on the velocity of gravitational movement of a grain flow in gravity flow with a diameter of 300 mm demonstrate a clearly pronounced nonlinear dependence on the height of the fall. This confirms the complexity of aerodynamic processes occurring during the free fall of grain in a gravity flow. At the initial stage (up to 10 m), an intense acceleration of the grain mass movement is observed. However, a further increase in height to 16 m does not lead to a proportional increase in velocity: it stabilizes. Such stabilization is explained by the increase in air resistance in the confined space of the pipe, which begins to balance the force of gravity. This value (13.25 m/s) actually approaches the velocity of wheat hovering, which indicates the achievement of a critical energy threshold, which confirms the conclusions of the study [22]. For engineering calculations, this means that the main destructive potential of the grain accumulates already in the first ten meters of the fall. Thus, the installation of braking devices on long vertical sections is not just advisable, but critically necessary to prevent increased grain injury.

The experimental results convincingly prove that the material of the contact surface is an influential factor in the process of absorbing the kinetic energy of the grain impact, which correlates with the results of research [29]:

- *Hardox 450 steel*: The use of this wear-resistant steel, despite its durability, is the most aggressive for the grain. With a direct impact (90°) from a height of 16 m, the level of injury reached a peak value of 0.6%. This is due to the high hardness of the material, due to which the impact energy is not absorbed by the surface, but is almost completely transferred to the fragile structure of the grain, causing massive micro- and macrocracks.
- *Polymeric materials*: The use of PE 1000 polyethylene and "ELASTOMER PZU 2319" polyurethane demonstrated positive dynamics. Polyurethane turned out to be 12% more effective than

steel. This is explained by its elasticity and ability to elastic deformation, which reduces peak loads on the endosperm.

– *The "grain-on-grain" method*: This option is the absolute leader in terms of injury-saving indicators, reducing the level of damage by 54–57% compared to steel. When forming a "grain cushion", the impact energy is divided between many grains. At the same time, some of the energy is spent on grain displacement and friction between grains. This is safer than hitting a hard surface.

The study confirms the direct relationship between the angle of inclination of the contact surface and the degree of grain destruction and complements the conclusions of studies [6, 9]. The most dangerous is a direct impact at an angle of 90°, at which the level of macrotrauma increases by 2.0–2.4 times. And when the angle is reduced to 30–45°, the force vector changes and the main part of the energy is spent on sliding friction, rather than on impact. This conclusion is important when designing grain gravity flow. Traditional vertical sections without intermediate slopes or cascades are the main sources of grain injury. Therefore, it is recommended to avoid contact angles close to 90°. It is recommended to replace them with cascade sections, where the grain speed is damped by multiple collisions at angles.

The use of the aniline dye staining method has proven its effectiveness, as indicated in [25]. This method allows for relatively easy detection of hidden damage to the grain, which is often ignored during simple (visual) inspection.

Endosperm: the detection of endosperm microtraumas in absolutely all modes of fall is informative. This is evidence that the structure of the endosperm, which contains a large amount of starch, is extremely fragile. Even if the grain visually looks intact, moisture and diseases can penetrate through internal microcracks during storage.

Germ: better protected, but its damage begins to increase sharply at heights above 10 m. This is especially true for soft wheat varieties, in which the germ is not completely covered by the shell.

Safe barrier: the work proves that a height of 4 meters is conditionally safe. Up to this mark, the number of macrotraumas and cracks remains small. This allows to maintain the quality of the grain at a higher level. This conclusion complements the study [2, 3].

Comparison with existing studies. The research results confirm other studies that indicate the importance of the physical and mechanical properties of the contact surface with the grain. However, previous studies often focused only on the quantitative assessment of grain injury, i.e. broken or intact. This research shows the degree of vulnerability of grain elements (micro- and macrotrauma of the embryo and endosperm).

Also, the data obtained on the effectiveness of polyurethane inserts (in our research, this is a 12% reduction in injury) complement the conclusions of the authors who proposed the use of rubberized plates. It is confirmed that elastic inserts are an effective tool for modernizing TTL.

Practical recommendations:

- it is necessary to limit the height of the free fall of grain to 4 meters or less depending on the hardness of the contact surface;
- in places where the direction of movement changes (knees, transitions) it is advisable to install polyurethane damping inserts.

At the stage of designing or modernizing the TTL, preference should be given to gravity-cascade installations or brake devices that ensure the fall of grain onto the "grain pillow" and allow maintaining the speed of grain movement within safe values, since this is the most effective method of trauma-saving technology for transporting grain.

Directions for further development of the research may be to expand the range of ambient air and grain temperatures, the influence of gravity flow tightness on the speed of grain movement and the degree of its damage during free fall, and conducting research on other crops that are less resistant to injury.

4. Conclusions

1. The speed of gravitational movement of the grain flow in the TTL gravity flow was determined. It was established that the dynamics of free fall of grain in a gravity flow is nonlinear. The most intensive increase in speed occurs on a segment up to 10 m, where it reaches 12.35 m/s. With a further increase in height to 16 m, the acceleration slows down significantly, and the speed stabilizes at 12.35–13.25 m/s, which approaches the critical hovering speed for this crop. This indicates that air resistance in a limited space of a gravity flow acts as a natural damper, but the accumulated energy is sufficient to initiate destructive processes in the structure of the grain upon collision with an obstacle.

2. When determining grain damage, it was proven that the type of material from which the working bodies of the TTL are made is a determining factor in the intensity of injury:

– *Hardox 450 steel*: It showed the highest aggressiveness. When falling from a height of 16 m, the injury level reached a maximum of 0.6% (when falling onto the surface at an angle of 90°). The high hardness of the material of the contact surface leads to almost complete transfer of impact energy to the external and internal tissues of the grain.

– *Polymeric materials (polyethylene and polyurethane)*: The use of high-molecular polyethylene reduces the level of damage by 7% compared to steel. Polyurethane lining turned out to be more effective, reducing injuries relative to a steel surface by 12% due to better cushioning properties and lower hardness.

– *The "grain on grain" principle*: It is the most trauma-saving method of transportation. The level of damage during such contact is the lowest. A reduction in the amount of grain injury by 54–57% relative to contact with a steel surface is recorded. This is convincing confirmation of the feasibility of designing stepped gravity flows and loading devices that form a "grain cushion". And in places where this is technologically impossible, elastic polyurethane inserts should be installed.

A direct relationship between the angle of incidence of the flow and the number of destroyed grains has also been proven. At an angle of inclination of the contact surface of 30–45°, the sliding friction force will prevail, which reduces the impact force of the grain. The critical angle is 90°, at which the level of macrotrauma and grain fracture increases by 2–2.4 times compared to more inclined areas of gravity flow. Therefore, it is necessary to avoid vertical areas of grain fall without using braking devices in the TTL.

At the stage of design or modernization of the technological line, it is recommended to give preference to gravity-cascade or braking devices that have the principle of grain falling onto a "grain pillow". This will allow maintaining the speed of grain movement within safe limits, which is the most effective method of trauma-saving technology for grain transportation.

3. An analysis of experimental samples was carried out and the degree of damage to the structural elements of the wheat grain was established. Endosperm microtraumas are recorded under all conditions of fall from 0.05 to 0.43%, which indicates a fragile internal structure. Damage to the embryo begins to actively manifest itself at a fall height of more than 10 m and sharp angles of collision in the amount of 0.06–0.3%. Macrotraumas and fractures are characteristic of heights of more than 4 m and increase in contact with harder surfaces in the amount of 0.1 to 0.19%. These factors have the greatest impact on the quality characteristics of the grain.

Conflict of interest

The author declares that he has no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Manuscript has no associated data.

Use of artificial intelligence

The author confirms that he did not use artificial intelligence technologies when creating the current work.

Authors' contributions

Ruslan Mirskykh: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review and editing, Visualization, Project administration.

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