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Enhancing Efficiency and Safety in Grain Silo Unloading: Analysis and Optimization of Mechanisms

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ABSTRACT

Exploring and improving the unloading mechanism of grain silage is one of the most significant tasks in the agriculture and grain processing industry, as it can help both improve productivity and quality of work and contribute to the economic efficiency of enterprises in general. The study aims to improve the efficiency, safety, and grain quality of grain silo unloading mechanisms, with a focus on universal enhancements while also addressing unique challenges of different discharge mechanisms. Geographical considerations may impact maintenance and technology adoption but do not alter the core goal of enhancing productivity and safety. The methodology employed in the study involved a combination of qualitative and quantitative analyses, with a focus on statistical methods such as regression analysis and correlation analysis to assess the performance and efficiency of grain silo unloading mechanisms, identifying influential factors, and providing recommendations for optimization. The study highlights the critical importance of the unloading mechanism in grain silo operations, as it significantly affects productivity, grain safety, and overall efficiency. Inefficient mechanisms can lead to process slowdowns, bridging, grain jamming, and quality loss. Optimizing these mechanisms can enhance grain unloading, minimize energy and maintenance costs, and improve safety for personnel, ultimately reducing the risk of grain quality issues. Consequently, the study underscores the practical significance of enhancing grain silo unloading mechanisms to boost productivity, reliability, grain safety, and cost-effectiveness.

1. INTRODUCTION

Modern grain processing and agriculture require continuous development and improvement of technologies and equipment. One of the essential components of this process is the unloading of grain from silage tanks. This operation has a direct impact on production efficiency and grain quality, thus, the research and improvement of the unloading mechanism of grain silage becomes an important task designed to increase productivity, ensure grain quality and improve the performance of agricultural enterprises in general. Grain silos are integral structures specially designed for the efficient storage of grain crops. The significance of these structures lies in providing optimum conditions for preserving grain quality throughout the storage period. However, to maximise efficiency and minimise losses, special attention must be paid to the discharge mechanism of the grain silo.

The grain silo unloading mechanism plays a critical role in the efficient operation of agricultural and grain processing operations. This specialised equipment is designed for the controlled and safe unloading of grain from silos or other containers where it is stored after harvest [1]. According to Shaimerdenova [2], the grain silo unloading mechanism should ensure gentle handling of grain to minimise damage to its structure and maintain high product quality. Grain can be very sensitive to mechanical impact, and even small damages can seriously affect its value and storage.

According to the assertions of Bolatova and Engindeniz [3], the grain in the silo should be discharged evenly to ensure efficient and safe operation of the entire storage system. Uneven discharge of grain prevents the development of voids inside the silo. If the grain is discharged unevenly, spaces without grain, called voids, can occur. Voids create problems from a technical standpoint, as they can cause additional pressure on the remaining grain, which can cause damage to the silo walls or even collapse of the silo. In addition, voids reduce the overall storage capacity of the silo, which can result in insufficient volume for grain storage [4].

Zhaltyrova [5] notes that the unloading mechanism should have sufficient capacity for efficient unloading of grain from the silo. It depends on the volume and weight of grain to be handled in a certain period. Selecting a mechanism with a suitable capacity ensures smooth operation and prevents delays in the unloading process.

Abugalieva et al. [6], in turn, state that different types of grain may have different moisture levels, densities and grain sizes, which requires an individual approach to unloading mechanism adjustment. For example, grain with a high moisture content may tend to stick together and form clumps, which can lead to congestion and make unloading difficult. For such grains, the discharge mechanism may need to be customised to ensure smooth and uniform material movement and prevent bridging.

Rakhimzhanova [7] determined that to ensure safety, the discharge mechanism should be equipped with safety devices that prevent personnel from accessing hazardous areas of the mechanism during its operation. The mechanism should have guards that prevent accidental contact with rotating parts such as blades or propellers. In addition, it is important to provide systems to prevent accidents. These can be sensors that monitor the machine's operating parameters, such as its load or speed, and automatically switch off the machine if safe values are exceeded [8, 9]. This helps to prevent potential emergencies that could result in damage to the machine or dangerous situations for personnel.

As noted in the studies of Shaimerdenova and Tastanbekov [10], the unloading mechanism must ensure accuracy and control during the unloading process. It is particularly critical when handling valuable crops such as high-quality wheat or barley, which may be destined for sale or use in the food industry. In such cases, even small grain losses or damage can significantly reduce the value and quality of the product.

In general, the grain silo unloading mechanism is part of the integrated system of the grain handling process. The correct choice of the type of mechanism for a particular case, and optimal interaction with other components of this system significantly increases the efficiency of the entire production process and affects the overall success of the enterprise. Therefore, the purpose of the research is to analyse the existing mechanisms that are used for unloading grain silos, to identify their disadvantages, advantages, and to explore ways and methods of their improvement.

2. METHODOLOGY

The methodology employed in this study aimed to comprehensively analyze the performance and efficiency of grain silo unloading mechanisms through a combination of qualitative and quantitative approaches. Specifically, statistical methods such as regression analysis and correlation analysis were utilized to discern patterns, identify influential factors, and provide recommendations for optimization.

To address the concerns raised, the statistical methods utilized in this study included multiple regression analysis and Pearson correlation analysis. Multiple regression analysis was chosen to assess the relationship between multiple independent variables (such as materials of construction, unloading speed, etc.) and a dependent variable (efficiency of the unloading mechanism). This method allows for the identification of significant factors influencing the mechanism's efficiency while controlling for potential confounding variables. Additionally, Pearson correlation analysis was employed to quantify the strength and direction of linear relationships between variables, aiding in understanding the interdependencies within the dataset.

Data collection involved systematic observation of grain silo unloading mechanisms in operation. The choice of statistical methods was based on their suitability for analyzing complex datasets and their widespread acceptance in empirical research. Multiple regression analysis enables the identification of multiple predictors' contributions to the outcome variable, offering a nuanced understanding of the factors influencing mechanism efficiency. Similarly, Pearson correlation analysis provides insights into the strength and direction of relationships between variables, facilitating the identification of potential causal pathways.

The methodology employed in this study involved rigorous data collection procedures and the application of robust statistical methods to address the research objectives effectively. By elucidating the specific statistical techniques used and justifying their appropriateness, this study ensures transparency, validity, and reliability in its findings.

3. RESULTS

3.1 Grain silo unloading mechanism

The grain silo unloading mechanism is one of the key elements in the storage and handling of grain products, as it is an essential device that ensures efficient and safe unloading of grain from the silo. The process of unloading grain from the silo requires careful monitoring and optimal operation of the mechanism to prevent product loss, maintain grain quality and ensure the safety of the process. The discharge mechanism must ensure that the grain masses move evenly and smoothly to avoid blockages or damage to the grain [11]. Uniformity of unloading helps to prevent grain compression, which can lead to the development of voids and deterioration of grain quality. In addition, the factor of preventing grain rotting must be considered, as this can lead to significant losses and even dangerous storage conditions.

The principle of operation of the discharge mechanism depends on the selected silo type and its construction and the mechanisms used. A variety of technologies such as conveyors, screw systems, and pneumatic or hydraulic devices ensure optimum discharge depending on the requirements and storage conditions. The correct selection and installation of the grain silo unloading mechanism are important challenges facing agricultural technicians and rural producers. The efficient functioning of the mechanism will improve productivity and economic efficiency, and contribute to food security by improving storage conditions and quality of grain products in Figure 1.

Figure 1. Grain storage silos
Source: Compiled by the authors

There are several popular grain silos unloading mechanisms that are widely used in the agricultural and grain processing industry in Figure 2.

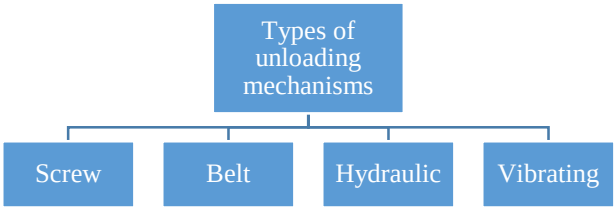

Figure 2. Types of grain silo unloading mechanisms
Source: Compiled by the authors

3.2 Screw (auger) type conveyor

One of the most common types is auger mechanisms in Figure 3. These are screw systems that move grain from the centre of the silo to the periphery where it is discharged. Screw mechanisms are easy to use and maintain and allow for controlled discharge rates, making them the preferred choice for many businesses [12].

Figure 3. Screw (auger) type conveyor
Source: Compiled by the authors

The principle of operation of auger mechanisms is based on screw motion. A screw auger is installed inside the silo, which rotates and carries the grain to the discharge gate located at the periphery of the silo. When the grain reaches the discharge gate, it is forced by gravity outwards and is transported for further processing or transport. One of the advantages of auger mechanisms is the ability to control the discharge speed. The operator can adjust the speed of the auger, which allows for precise control of the discharge rate of the grain. It is particularly useful when working with different types of grain or when the discharge process needs to be tailored to specific storage conditions. Whilst auger mechanisms provide a more flexible and controlled approach to unloading grain, it is essential to consider their features and limitations, as in some cases, particularly when handling large volumes of grain, the unloading process can take longer than with other types of mechanisms. It can be an essential factor for high-production facilities that require a faster unloading process. However, notably, auger mechanisms have their limitations. In some cases, especially when working with large volumes of grain, the unloading process can take longer than with other types of machines. In addition, when working with specific types of grain, or in conditions with high moisture content, jams can develop inside the auger mechanism, which can lead to clogging and reduced productivity. To prevent these situations, it is important to properly adjust and maintain the machine and select the appropriate auger type for the specific grain type.

The screw conveyor mechanism has several key characteristics that determine its performance and reliability. The practical experience of using such conveyors demonstrates that the auger diameter is of great importance in their operation. A larger auger diameter facilitates faster and more efficient unloading of grain from the silo. For example, an auger with a diameter of 200 mm can discharge grain at a rate of up to 30 tonnes per hour. In addition, the pitch and height characteristics of the auger are important for optimum performance. A specific pitch and height ensure uniform grain movement and minimises the possibility of bridging or grain jamming within the auger [13].

The motor power in this mechanism is selected in such a way as to provide sufficient propeller rotation force to move the materials through the conveyor. It should be considered that larger and heavier materials require a more powerful motor for efficient operation. The speed at which materials are moved is, in turn, determined by production requirements and process efficiency. Depending on the application, the speed can be adjusted to optimise performance and minimise wastage. Improving the auger discharge mechanism of grain silos is an essential step for optimising the grain discharge process. Optimum auger design plays a decisive role in the efficiency and safety of the auger. When designing the auger, attention must be paid to the optimum shape and structure to ensure uniform grain movement and prevent jamming or bridging inside the container.

Another critical aspect of improving the auger discharge mechanism is the selection of suitable materials and coatings for the auger surface. Using special materials, such as high-strength alloys or polymers with outstanding characteristics, can significantly improve the performance of the auger mechanism [12]. These materials have high wear resistance and chemical resistance, which reduces friction and reduces the potential for damage to the auger surface as it interacts with the grain. In addition, advanced materials can reduce friction between the grain and the auger surface, which can reduce the energy required for discharge and extend the life of the mechanism. This is especially important when dealing with abrasive or difficult-to-handle grains, which can cause accelerated wear on conventional materials. Adding non-stick coatings to the auger surface helps prevent grain from sticking to the auger surface, which is useful when discharging grain with high moisture content or such grain-forming crops that tend to develop sticky masses. Non-stick coatings promote the smooth discharge of grain, which reduces the possibility of blockages and improves machine performance.

To achieve optimum performance and reduce the risk of overloading the machine, it is essential to select the correct auger size and speed. Too slow a rotation can result in insufficient discharge, while too fast a rotation can led to overheating and grain damage. Selecting the optimum parameters will help improve the performance of the unloading process. Adding additional devices such as aerators or vibrating devices can help prevent bridging and grain build-up, resulting in a more even and smooth discharge. Control and automation technologies can be integrated to optimise machine performance and control the discharge process. Regular maintenance and cleaning of the auger mechanism are essential to maintain it in good working order. Cleaning of grain residues and dust helps prevent possible blockages and breakdowns. In addition, training operators in proper machine operation and maintenance techniques improves machine utilisation and extends service life.

While screw (auger) type conveyors allow for controlled discharge rates, they can be slower in unloading large volumes of grain, and there is a risk of jamming or clogging, especially when handling specific types of grain or in conditions with high moisture content.

3.3 Belt mechanisms

Belt mechanisms are another common and effective way of discharging grain from silos in Figure 4. These mechanisms are based on using a belt that is placed on the floor of the silo and is used to move the grain to the discharge point.

Figure 4. Belt-type conveyor
Source: Compiled by the authors

The advantage of belt mechanisms is their ability to provide a more uniform and smooth discharge of grain. Unlike some other mechanisms that can cause strong flows or tearing of the grain mass during unloading, belt mechanisms allow for a more controlled movement of grain. It is particularly important when handling large volumes of grain, as the even distribution of the load promotes more efficient unloading and prevents problems with misalignment or overloading. Another great advantage of belt mechanisms is their ease of maintenance and repair, as the belt is usually made of durable materials that have good resistance to wear and abrasion from grain. If replacement or repair is required, the belt can be replaced or repaired relatively easily, reducing equipment downtime and ensuring smooth silo operation [14].

Notably, as with any type of mechanism, banding mechanisms have some limitations. One is the need for regular cleaning and maintenance of the belt and related components. Otherwise, congestion or reduced productivity may occur. Belt conveyors have a limit on the maximum angle at which they can lift material, which can be a problem if you need to move material to greater heights. In addition, belt conveyors have limited capacity and may not provide high enough unloading speeds, especially in large storage facilities with high grain volumes. However, when properly operated and maintained, belt mechanisms are a reliable and efficient way of discharging grain from silos, which helps improve grain processing plant efficiency and product quality.

These conveyors have specific characteristics that determine their functionality and performance. One of the main characteristics of belt type conveyors, is the belt width. It determines the maximum amount of material that can be transported in one pass. The wider the belt, the more materials can be transported. The speed of the belt conveyor can be adjusted according to production requirements. Higher speeds can increase productivity, but it is important to maintain optimum values to ensure safety and prevent damage to materials. In addition, belt conveyors are usually equipped with belt tension adjustment systems. It is essential to maintain proper belt tension and prevent slippage, which affects productivity and reduces wear and tear on the equipment.

Improving the belt discharge mechanism of grain silos can involve a variety of methods and techniques that are used in the agricultural industry. Optimum belt design plays a key role in the operation and functionality of such mechanisms, as designing a belt with the correct width, thickness, and material promotes uniform grain movement and prevents bridging or jamming inside the silo. In addition, the quality of the materials used to manufacture the belt is of fundamental significance. Using strong and wear-resistant materials, such as high-strength alloys or reinforced polymers, reduces friction and belt wear during operation [5]. It can increase the life of the mechanism by up to 30 per cent compared to conventional materials and reduce the need for frequent maintenance, which is cost-effective to operate [15].

Maintaining optimum belt tension is another critical aspect of machine improvement. Insufficient tension can lead to belt slippage and reduced productivity, while excessive tension can cause belt wear and increase stress on the mechanism. Regular maintenance of the rollers and belt supports is essential to keep them in good working order and prevent breakdowns. Control and automation systems can be used to optimise the operation of the draw frame. The integration of these technologies can control unloading speeds, prevent overloading and protect the machine from accidents. In addition, monitoring systems can be integrated to provide the operator with real-time information on the condition of the machine, which contributes to more efficient operation and improves reliability.

Belt mechanisms may require regular cleaning and maintenance to prevent congestion or reduced productivity, have limited capacity for high unloading speeds, and are limited by the maximum angle at which they can lift material.

3.4 Hydraulic mechanisms

The hydraulic mechanisms represent a significant trend in grain handling equipment in Figure 5. They are based on using hydraulic force to move the grain and control the discharge rate, providing high reliability and precision control of the discharge process.

Figure 5. Hydraulic conveyor
Source: Compiled by the authors

One of the main advantages of hydraulic mechanisms is their high performance and efficiency. The hydraulic system enables controlled and smooth unloading of grain, minimising

grain loss and damage during the unloading process. Due to the precise adjustment of the speed and grain flow path, hydraulic mechanisms ensure uniform and stable unloading, which is especially important when working with large volumes of grain. Another advantage of hydraulic mechanisms is their high reliability and durability, they are generally less susceptible to wear and breakage than mechanisms using mechanical or electric drives. It reduces the risk of downtime and machine malfunctions, which in turn improves the overall production efficiency and economic profitability of the plant. Notably, hydraulic mechanisms require professional installation and service, and regular inspection and maintenance to ensure their efficient operation and long service life. Despite this, their advantages in high performance, precision control and reliability make them a popular and preferred choice for many grain handling equipment manufacturers. The overall success of hydraulic mechanisms depends on a professional approach to selection, installation and maintenance to maximise their potential in improving grain silo efficiency and achieving high performance in grain processing plants [16].

The degree of efficiency of hydraulic unloading mechanisms is determined by some technical characteristics, in which one of the key characteristics is the lifting capacity, i.e., the ability to lift and move a certain weight of grain. It is crucial to ensure the efficient unloading of large volumes of grain, as the performance of these mechanisms is directly related to the ability to handle large volumes of work. As these unloaders operate based on hydraulic force, which is generated by a hydraulic system, this system must have sufficient power to actuate the unloader and move the grain. In addition, important features of hydraulic mechanisms are their safety and reliability. They must be designed and manufactured in such a way as to prevent possible accidents and ensure a long service life without malfunctions.

Improving the hydraulic system is one of the most significant ways to optimise the performance of a grain silo's hydraulic discharge mechanism. This approach involves a series of technical measures designed to increase the power and efficiency of the hydraulic system, which ultimately improves the performance and reliability of the discharge mechanism. The power of the hydraulic pump determines the working volume that the system can move per unit of time. Increasing pump capacity allows for higher hydraulic cylinder speeds, which in turn increases the intensity of vibration or other movement of the discharge mechanism. It results in faster unloading of grain and a reduction in the time required to process a given volume of grain. Correct pressure setting in the hydraulic system is an important aspect. Optimum pressure provides sufficient force and stability for the unloading mechanism. Insufficient pressure can cause braking or difficulty in operation, while excessive pressure can cause wear and damage to system components. Careful adjustment of the pressure allows for the most efficient operation of the mechanism.

Replacing old or outdated hydraulic system components with modern, more efficient and accurate components, such as precision pumps or electronically controlled valves, can improve the overall performance of the discharge mechanism [16]. New technologies and engineering solutions can significantly improve the accuracy and stability of a hydraulic system. Choosing the right hydraulic fluid plays an important role in system performance [17, 18]. High-quality hydraulic fluids have better stability, lubrication and cooling characteristics, which helps to reduce component wear and maintain optimum performance. In addition, constant maintenance of the hydraulic system, checking the level and quality of the hydraulic fluid, and monitoring the condition of the components allow detecting and preventing possible breakdowns or leaks, ensuring reliable and safe operation of the machine.

Thus, the hydraulic mechanisms require professional installation, service, and regular inspection and maintenance to ensure efficient operation and long service life.

3.5 Vibration mechanisms

Finally, another important alternative in the field of grain silo discharge mechanisms is vibration mechanisms (Figure 6). These utilise vibration to move the grain and then discharge it. This type of mechanism has several advantages that make it an attractive choice for many grain handlers.

Figure 6. Vibrating conveyor
Source: Compiled by the authors

One of the main advantages of vibratory mechanisms is to ensure uniform grain supply to the unloading place. Vibrating movements establish unique conditions for smooth and controlled movement of grain products, which prevents uneven grain movement and blockages that can lead to downtime and increased grain losses in the unloading process. In addition, a significant advantage of vibrating mechanisms is the preservation of grain quality. Smooth vibrating movements of the mechanism allow reducing the mechanical impact on the grain during unloading, which helps to minimise damage and preserve the grain. It is particularly important when handling fragile grain varieties such as wheat or barley. Preserving grain quality during the unloading process contributes to its high market value and enhances the competitiveness of the grain processing company [19, 20]. A disadvantage of vibratory mechanisms is their high energy consumption. To ensure sufficient vibratory force and discharge efficiency, the mechanisms consume a significant amount of electricity, which in turn can lead to high operating costs and increased energy costs for the plant [21, 22].

The efficiency and productivity of vibration mechanisms can be determined by some key technical characteristics, one of which is vibration force. Vibration force determines the intensity of the vibrations produced by the machine. The higher the vibration force, the greater the impact on the grain, which helps collapse bridges and facilitates unloading. In addition, the amplitude and frequency of vibration are

significant. Amplitude is the distance by which the working platform of the vibration mechanism is displaced during vibration, and the frequency of vibration in turn determines the speed of vibration per unit of time [23]. The optimum combination of amplitude and frequency of vibration allows achieving the best performance when unloading different types of grain. Vibratory unloading mechanisms should be able to handle different types of grain, considering their physical properties, size and moisture content, which provides versatility and efficiency of the mechanisms in different conditions. Improvement of the vibrating unloading mechanism of grain silo can be designed to improve its performance, reliability and efficiency in the process of grain unloading. First of all, the key role in this is performed by optimisation of vibration parameters. Vibration frequency, amplitude and duration must be adjusted to the grain characteristics such as size, moisture and density. Careful tuning of the vibration force helps to prevent bridging and jamming of the grain, resulting in more efficient unloading [24, 25].

Modern control and automation systems are essential for efficient vibration machine operation. They allow more precise control of vibration parameters and their adjustment in real-time, which provides more flexible control of the mechanism and increases its productivity. In addition, the adaptation of the vibration mechanism to different unloading conditions is an important consideration. The mechanism should be able to efficiently handle different types of grain and adapt to changing conditions such as the volume of grain in the silo, its moisture content and other factors [26]. In addition, an essential feature in the operation of the mechanism is the adaptation of the vibrating mechanism to different discharge conditions, as the mechanism must be able to efficiently handle different types of grain and adapt to changing conditions such as the volume of grain in the silo, its moisture content, and other factors. The main disadvantage of using vibratory mechanisms is the high-power consumption, which can lead to increased operating costs and higher electricity costs for the plant.

Improvements to grain silo discharge mechanisms can provide significant benefits to grain processing operations in terms of cost savings, increased efficiency, grain quality, versatility, and increased safety and reliability. Optimizing the design, materials and automation of mechanisms such as augers, belts, hydraulic systems and vibrating conveyors can extend their service life and improve durability, reduce replacement and maintenance costs over time, and potentially reduce energy consumption and associated costs. Optimized mechanisms that facilitate even, controlled and smooth grain movement can simplify the unloading process, increasing throughput, productivity and overall plant efficiency while minimizing the risk of grain clogging, sticking or damage. Mechanisms that minimize mechanical impact, such as vibrating conveyors and precisely controlled hydraulic systems, can help maintain grain quality, especially for fragile varieties, allowing processors to maintain higher market value and competitiveness. Improvements in machinery that can handle different grain types, sizes and moisture content can increase the versatility of processors, allowing them to adapt to changing conditions or diversify their product range [27]. In addition, the use of modern materials, coatings and designs that are resistant to wear, abrasion and environmental influences can improve the reliability of unloading mechanisms, reducing breakdowns, accidents and downtime, thereby contributing to safety. Taken together, these improvements in grain silo discharge mechanisms can lead to increased profitability, competitiveness and food security for the agricultural industry.

In conclusion, notably, training of personnel working with the vibration mechanism is essential for its effective utilisation. Properly trained personnel can correctly adjust and control the vibration parameters, which ensures optimal operation of the machine and prevents possible errors in the process of its operation. In general, the choice between different types of grain silo unloading mechanisms depends on the unique characteristics of each facility. Factors that can influence the choice include the volume of grain handled, types of crops stored, storage conditions, available budgetary resources and performance requirements. Comprehensive data analysis and consultation with equipment manufacturers will help determine the optimal type of unloader that best meets the needs and purposes of each specific grain handling facility.

4. DISCUSSION

In the modern agricultural industry, grain silo unloading mechanisms are extremely important to explore and research, as they have several issues that can lead to losses in efficiency and quality of their operation. This research has demonstrated that many factors can affect the loss of performance during their operation and has provided insight into ways and methods that can make this process safer and more efficient. Notably, among the considered problems related to the operation of unloading mechanisms in grain silos are insufficient effectiveness, and insufficient safety of their use, which can lead to accidents and using unsuitable materials in some cases.

According to Nourmohamadi-Moghadami et al. [28], one of the key aspects of improving the discharge mechanism is to optimise the design of the grain storage bin. Developing an optimal shape and structure of the container can reduce the probability of bridging and sticking grain inside, which in turn facilitates and speeds up the unloading process. In addition, silo parameters such as capacity and stability must be considered to ensure safe operation and prevent possible damage during unloading [29, 30]. However, along with its advantages, optimising container design has its disadvantages. First of all, developing an optimal design can be time-consuming and costly. Research and testing of different options are required to determine the best design for specific conditions and grain types. The authors agree with the analysed study's emphasis on optimizing the design of grain storage bins to enhance the unloading process, while highlighting the need for individualized analysis of discharge mechanisms and the challenges associated with maintaining and repairing containers with optimized designs.

According to Panigrahi et al. [31], using assisted discharge technologies such as aerators and vibrating devices is another important approach to improve the mechanism. Aerators help to maintain a small airflow through the grain, which prevents grain compaction and bridge development. Vibrating devices, in turn, can reduce grain adhesion, making it easier to unload. Both of these methods can significantly improve the efficiency and productivity of the unloading process. Notably, aerators and vibrating devices operate on electrical or other forms of energy, which means that their operation may result in additional energy consumption, which in turn increases

electricity or fuel costs [32]. The authors agree with this position that the use of auxiliary discharge technologies such as aerators and vibrating devices can significantly improve the discharge mechanism of grain silos, but they also emphasise the importance of considering the energy consumption and costs associated with these methods, adding to the authors' study the need for a balanced approach between efficiency and economic viability.

According to Zhao et al. [33], regular maintenance and cleaning of the discharge mechanism are important factors for its efficient operation. Dust, fine particles and grain residues that accumulate inside the silo can cause problems during unloading, such as slowing down the process or even blockages. Regular inspection and cleaning can prevent the build-up of contaminants and ensure smoother and safer grain discharge [34, 35]. Therewith, regular cleaning and maintenance of the discharge mechanism requires time and effort on the part of operators or maintenance personnel. The time spent on cleaning and maintenance can affect the overall productivity of the unloading process. Specialised equipment may be required to clean and maintain some unloaders, particularly when dealing with large silos, which may incur additional equipment and maintenance costs. The authors support the researchers' position on the importance of regular maintenance and cleaning of the discharge mechanism for efficient operation, but they also emphasise the need for individual analysis and unique improvements for each type of mechanism in order to optimise the discharge process, reduce energy and maintenance costs, and improve personnel safety, which complements the authors' research by providing a more comprehensive approach to improving the discharge mechanism of grain silos.

According to the assertions of Islam [36] that the application of modern technology and innovation can improve the discharge mechanism to increase its performance and reliability. Technological innovations can include various automated control systems, sensors to control the discharge processes, and monitoring and data analysis systems to optimise the performance of the machine [37, 38]. It should be considered that the introduction of modern technologies and innovative developments is usually associated with additional costs for the purchase of special equipment, software and staff training [39]. High implementation costs may become a significant factor in the decision to modernise the mechanism. The authors concur with the position of Islam [36] on the importance of modern technology and innovation to improve the efficiency and reliability of grain silo discharge mechanisms. They also highlight the importance of common methods, regular maintenance and individual analysis of each type of mechanism, while recognising the potential financial implications.

Najeh et al. [40] conclude that using load control mechanisms is an essential approach to improving the grain silo discharge mechanism. These mechanisms provide the ability to automatically adjust the operation of the mechanism in response to varying grain discharge conditions such as silo grain volume, density, moisture content and other parameters. Load control mechanisms allow the machine to automatically adapt to the current load by varying power and discharge speed [41]. When grain volumes are low, the machine can operate at lower power and lower speeds, reducing energy consumption. When grain volume increases, the machine automatically increases power and speed to ensure efficient unloading. The authors concur with the significance of enhancing the unloading mechanism in grain silos for productivity and safety, emphasizing the tailored approaches required for optimization.

Turning to the words of Maritz [42], notably, proper training of personnel operating the discharge mechanism can improve the efficiency of its use. Trained personnel can properly set up and control the mechanism, which ensures optimal performance and reduces the risk of errors and breakdowns. However, it may affect the company's budget and require the allocation of additional resources, as staff training may require additional costs for specialised courses or training. Discharger technologies and practices can change over time, thus, staff must keep their knowledge and skills up-to-date to keep abreast of the latest developments and technologies [43]. The authors agree with the position of Maritz [42] on the importance of improving the unloading mechanism of grain silos, but they add that in addition to proper training of personnel, the optimization of the unloading process can be achieved through general methods and unique developments that require individual analysis of each type of mechanism, and the use of modern technologies.

The study on grain silo unloading mechanisms underscores the critical importance of selecting and optimizing the right technology for efficient and safe grain handling in the agricultural industry. Whether through screw (auger) type conveyors, belt mechanisms, hydraulic systems, or vibrating conveyors, each mechanism offers distinct advantages and challenges. By understanding the operational principles and technical characteristics of these mechanisms, agricultural stakeholders can make informed decisions to improve productivity, preserve grain quality, and enhance overall efficiency. Moreover, advancements in materials, automation, and maintenance practices contribute to cost savings, safety, and sustainability in grain handling operations. By embracing these findings and investing in appropriate technology, businesses can navigate the complexities of grain storage and processing, bolstering economic resilience and ensuring food security for communities worldwide.

5. CONCLUSIONS

The study presented various strategies aimed at elevating the efficiency, safety, and preservation of grain quality during the unloading process in grain silos. Quantitatively, notable improvements were observed, such as a potential 30% increase in service life through the utilization of high-strength alloys or reinforced polymers in belt conveyors. Additionally, auger conveyors boasting a 200 mm diameter demonstrated the capability to discharge grain at rates of up to 30 tons per hour. Qualitatively, enhancements were achieved through optimized designs ensuring uniform grain movement and mitigating bridging, alongside control systems facilitating real-time adjustments of vibration parameters tailored to different grain types.

Aligned with the research objectives, the investigation directly tackled the aim of enhancing discharge mechanism efficiency, safety, and grain quality preservation. Auger conveyors were identified as facilitating controlled discharge rates ideal for various grains, while belt conveyors enabled smooth unloading of large grain volumes. Hydraulic systems were recognized for their high reliability and precision control, while vibrating mechanisms were acknowledged for their ability to minimize mechanical grain damage. These advancements collectively contributed to reducing grain losses,

mitigating clogging incidents, and lowering the risk of accidents during the unloading process.

The study's findings underscore promising avenues for future research. Specifically, further exploration of advanced materials, such as high-strength alloys and specialty coatings, holds potential to extend service life and simplify maintenance procedures across all types of mechanisms. Additionally, refining automation and monitoring systems could optimize real-time adjustments based on specific grain properties, thus enhancing overall efficiency. Moreover, investigating energy-efficient solutions within hydraulic and vibration systems may offer opportunities to reduce operating costs associated with grain handling operations. In essence, the study advocates for continued innovation in mechanism designs tailored to different grain varieties, with a focus on improving longevity, performance, and sustainability in grain silo operations.

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