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OPTIMISATION OF TECHNOLOGICAL PARAMETERS OF CENTRIFUGAL IMPACT CRUSHERS FOR GRAIN GRINDING

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ABSTRACT
This study aims to increase the energy efficiency and product uniformity of centrifugal impact crushers for feed grain processing through targeted optimisation of technological parameters. A direct-impact mechanism was implemented by profiling the stationary impact lining with an involute tooth geometry that ensures grain collisions at a 90° angle, minimising kinetic energy losses. Experimental tests were conducted on pea grain (moisture 11.6%) using a prototype crusher developed at Kostanay Regional University. Rotor speed was set at 2000 rpm, throughput maintained at 400 kg/h. The optimised crusher achieved a specific energy consumption of 2.89 kWh/t, which is 22% lower than a conventional impact crusher of similar capacity. The crushed product had an arithmetic mean particle size of 1.31 mm with 85% of particles within the 0.5-1.5 mm range, meeting zootechnical standards. Theoretically, this work refines comminution models by quantifying the effect of impact angle on breakage efficiency and provides a design criterion (involute profile with 47°-56° contact angles) for normal-impact crushers. Practically, the prototype offers a low-energy, high-uniformity solution suitable for feed mills and can be retrofitted into existing machines. The main contribution is the experimental validation that deliberate alignment of impact geometry reduces specific energy by over one-fifth without sacrificing throughput or quality, opening a new direction for energy-efficient grinder design.

Keywords: *Centrifugal-Impact Crushers, Grain Grinding, Energy Efficiency, Impact Angle, Involute Profile*

1. Introduction

Centrifugal impact crushers are essential in feed production because they combine high throughput with significantly lower energy consumption than traditional hammer mills. Modern agriculture demands efficient grain grinding: feed milling accounts for 15-20% of total electricity use in livestock operations (Marczuk et al., 2019). Improving crusher efficiency by just 10% could save hundreds of GWh annually worldwide. Despite their advantages, conventional centrifugal impact crushers still exhibit two major shortcomings: (1) oblique grain impacts that dissipate 15-20% of input kinetic energy as heat and friction, and (2) poor performance with high-moisture (>17%) or oily grains due to clogging and smearing on flat impact surfaces.

The scale of the energy challenge in industrial processing is substantial. As a parallel example, Spunei et al. (2022) highlighted that suboptimal lighting systems in large-scale facilities account for a significant portion of total energy consumption, a problem that structured analysis and optimization can effectively address. This underscores the universal relevance of energy efficiency as a primary criterion in engineering design, whether for lighting or, as in our case, for mechanical comminution.

The state of the art has seen various incremental improvements. Iskakov and Gulyarenko (2025) introduced an air-assisted discharge that reduced dust fraction to 5.7% but did not alter the impact geometry. Marczuk et al. (2019) used multifactorial design to optimize blade count and gap settings, achieving a 12% energy reduction. Chen et al., (2023, 2025) demonstrated via DEM that glancing impacts waste a large portion of energy, yet their work remained simulation-based. None of these studies proposed a geometric criterion for ensuring a pure normal (head-on) impact. Consequently, a clear knowledge gap exists: how to design the impact surface so that every grain strikes it perpendicularly, and what energy savings can thereby be achieved.

The core problem is therefore the absence of a validated, hardware-implemented normal-impact design for centrifugal grain crushers. Classical comminution theories (Rittinger, 1867; Kick, 1885; Bond, 1952) assume isotropic energy distribution and do not account for impact angle. In free-impact theory, the useful work

$$\boldsymbol{A = (0.98 - 0.99)T}_0$$

only when the collision angle is 90° (Satone et al., 2022). Any deviation reduces the effective work by a factor of $\cos^2\theta$. This theoretical insight, however, has never been translated into a practical crusher geometry for feed grains.

To solve this problem, we propose a crusher whose stationary impact lining is shaped as an involute gear profile. The tooth geometry (47° near the base, 56° near the tip) ensures that a grain flying radially from the rotor hits the lining at 90°. We hypothesize that this direct-impact design reduces specific energy consumption by at least 20% compared to conventional flat-plate crushers while maintaining or improving particle size uniformity.

The novelty of this work is fourfold: (1) first experimental implementation of an involute-profiled impact ring for grain crushers; (2) quantitative correlation between impact angle and energy efficiency; (3) new classification of impact crushers based on impact normality; (4) demonstration that the design enables processing of dry peas (11.6% moisture) with record-low 2.89 kWh/t.

Accordingly, the research questions are:

- RQ1: How can an involute profile be designed to achieve a 90° grain impact?
- RQ2: What is the actual reduction in specific energy consumption (kWh/t) compared to a conventional crusher?
- RQ3: How does the direct-impact mechanism affect particle size distribution and product uniformity?

2. Literature Review

Grain grinding for animal feed is a fundamental yet energy-intensive process in agriculture. Traditionally, hammer mills (impact disintegrators) dominate this domain, but they are characterized by high specific energy consumption and uneven particle size distribution. Research since the late 20th century has sought to improve grinding efficiency; over 6,000 grain-crushing patent applications have been filed worldwide since the 1980s, underscoring continuous innovation in this field. The need for better designs is driven by practical challenges: increasing energy costs, the push for higher throughput, and stricter quality requirements for feed particles.

Conventional hammer and rotary crushers exhibit several well-documented drawbacks. They tend to waste energy as heat and friction, produce a broad particle size distribution (including excess fine dust), and suffer from rapid component wear. Specifically, hammer crushers require heavy metal components and still yield a high dust fraction and uneven grind. Their performance declines when grain moisture content rises (above 17%), often making it impossible to grind high-moisture grains or oilseeds like rapeseed. By contrast, impact centrifugal crushers (Nguyen & Hai, 2024) have a simpler design and can be more energy-efficient. Studies indicate that impact-type grinders can reduce specific energy use by roughly 1.5-2 times compared to hammer mills. However, early designs of impact centrifugal crushers had limitations: multi-stage centrifugal grinders sometimes experienced low throughput due to material clogging, and some designs exhibited high specific energy requirements despite theoretical advantages. For instance, a known multi-rotor crusher with concentric blades achieved finer grinding but at the cost of efficiency. These issues highlighted the need to optimize both the operational parameters (e.g., feed rate, rotor speed, gap settings) and the structural parameters (rotor and blade design, presence of baffles or secondary impact surfaces).

To ensure a comprehensive and current review, we searched Scopus, Web of Science, and Google Scholar using the keywords «centrifugal impact crusher», «grain grinding», «energy efficiency», «impact angle», «involute profile», and «feed processing». Only peer-reviewed journal articles published between 2020 and 2026 were included, supplemented by seminal older works (e.g., Nikolov, 2002) and relevant patents (2013-2020) to illustrate design evolution. After screening 87 records, 45 were selected for citation. This review identifies three persistent gaps that directly motivate our research questions:

i) absence of a validated design for normal-impact geometry (RQ1);
ii) lack of field-test data comparing energy use under controlled impact conditions (RQ2);
iii) no theoretical framework linking involute profile parameters to breakage uniformity (RQ3).

Researchers have explored various innovative designs to overcome the above drawbacks. Thus, the authors Savinykh et al. (2025) proposed a broad classification of impact crushers by acceleration method (centrifugal vs. inertial), grinding mechanism (free impact vs. abrasive or reflective), and type of working body (drum, rotor, hammer, or disc). This classification helped group diverse designs by their grinding process rather than form, clarifying development directions. Based on such analyses, new prototypes were introduced. For example, Nikolov (2002) investigated a counter-rotating double-rotor impact crusher in which two rotors with flat blades rotate in opposite directions to enhance particle collision rates. This counter-rotation aimed to increase grinding intensity and uniformity. Iskakov and Gulyarenko (2025) proposed combining multiple processes - cutting, impact, and sifting - into a single grinder to minimize auxiliary operations. Their design essentially hybridized cutting blades and impact elements, showing that multi-action grinding can improve efficiency by pre-cutting grains before impact and quickly removing finished product by sieving.

In Kazakhstan, local researchers have significantly contributed to the optimization of design. Kurmanov et al. (2013) patented a pea crusher with a novel blade configuration. In this design, the impact face of each rotor blade is tilted backward (at an angle α to the vertical), creating a slicing impact, and stationary «inner destruction» rings are added inside the crushing chamber. The backward blade tilt ensures that grain kernels strike the impact surface perpendicularly, implementing a «direct impact» principle. Meanwhile, the stationary inner rings act as additional impact surfaces, causing the grain to ricochet and be hit multiple times. This innovation aimed to increase crushing efficiency by optimizing the impact angle and providing more collision opportunities without a complex multi-rotor setup. Another patent by Kurmanov's team (2013) presented a disk crusher that differs from classical hammer mills. It features a rotating disk with hinged trapezoidal hammers (flails) that swing outwards by centrifugal force. Surrounding the hammers are concentric, stationary, serrated plates with triangular tooth profiles. Grain is drawn in by the vacuum (suction) effect of the spinning disk and crushed between the swinging hammers and the serrated stationary «combs». This design improved upon earlier disc crushers by using removable toothed plates (to extend service life) and by relying on airflow-induced feeding rather than forced feeding. The outcome was a more productive and maintainable crusher, with higher throughput and easier fabrication, addressing the issue of clogged material channels found in older designs. These Kazakhstan innovations exemplify how adjusting blade geometry, introducing secondary impact elements, and leveraging airflow for feeding can markedly improve crusher performance.

In recent years, researchers globally have employed systematic experimental and computational methods to optimize crusher parameters. A notable example is the work by Marczuk et al. (2019), who designed a rotary-centrifugal grinder and used a multifactorial experimental design to determine the optimal settings. They investigated factors including grain feed rate, rotor speed, the opening size of the separating screen, number of blades on inner and outer rotor rings, blade sharpness, and the presence of special inserts. Their optimization criteria were energy consumption and throughput (as well as product quality, measured by the fraction of coarse particles >3 mm). The multifactor analysis revealed that specific structural parameters have the most significant influence: the clearance (gap) of the separating surface and the condition/number of blades were among the most critical factors affecting power draw and output quality. They found that using fewer blades in the first stage of a two-stage rotor improved performance across all metrics, likely by reducing airflow drag and over-grinding. Additionally, ensuring that blades were sharp and properly arranged was critical to energy efficiency. This study demonstrated that statistical design of experiments is a powerful approach for fine-tuning crusher designs, enabling the identification of non-obvious interactions between variables. Similarly, Bilous et al. (2025), Dudin et al. (2025) conducted experiments on a rotary-centrifugal shredder and confirmed that addressing known shortcomings (high dust and uneven grind) requires holistic optimization of the design and kinematics. By varying rotor speed, feed rate, knife counts, and other factors, they developed mathematical models to predict performance. They demonstrated that a proper combination of these parameters eliminates many traditional drawbacks (such as the need to remove product to avoid over-milling swiftly).

Another line of research focuses on improving the material flow through the crusher. Mezenov et al., (2025) introduced a centrifugal-impact crusher with enhanced airflow that illustrates this approach. They added an auxiliary air intake in the loading neck, which forces additional air at - 4.8 m/s into the grinding chamber. This seemingly simple change had profound effects: the extra air dramatically increased the air velocity at the discharge (by 1.8 - 13 times, depending on rotor speed). It helped to «evacuate» crushed material more rapidly. By preventing ground grain from lingering in the chamber, the machine avoids over-grinding and reduces clogging. As a result, their new design achieved high-quality coarse grinding while consuming less energy. They report a maximal throughput of 1,440 kg/h and a minimum specific energy consumption of 2.1 W*s/kg per grinding unit (a metric combining energy and degree of grinding) under optimal conditions. Notably, this energy requirement was 1.22-1.89 times lower than that of conventional hammer crushers (when chopping barley). Additionally, the undesirable fine «dust» fraction under their optimal setup was below 5.74%, about half that produced by a standard hammer mill. These figures confirm that design modifications, such as improved ventilation and optimal sieving, can significantly outperform traditional mills in both efficiency and product quality.

Iskakov and Gulyarenko (2025) approached optimization from another angle: determining the optimal spacing (gap) and rotor speed in an impact crusher for wheat grain. Through experimental trials, they measured how crusher performance (throughput in kg/h) and specific work (energy per kg) vary with the adjustable gap at different rotor speeds. Their findings included characteristic curves showing that a too-small gap leads to congestion and high energy use (due to over-crushing and friction). In contrast, a too-large gap reduces grinding action, lowering quality. They identified an optimal gap setting that balances these effects, yielding a quality product at minimal energy cost. Although the optimal value depends on their crusher and wheat, the general insight is widely applicable. Every crusher has a sweet spot in configuration where it runs most efficiently, and systematic testing or modeling is needed to find it.

In a study directly relevant to post-grinding processing, Primawati et al. (2025) investigated the performance of a horizontal ribbon mixer, concluding that a mixing time of 10 minutes with a 75% fill level and 120 rpm rotor speed yields optimal homogeneity. While their work focuses on mixing rather than grinding, the identified operational parameters (time, fill level, speed) are analogous to the optimization challenges faced in centrifugal crushing, reinforcing the importance of multi-parameter factorial design.

The quest to optimize crushers has also benefited from modern simulation and modeling tools. Researchers employ Finite Element Analysis (FEA) to examine stress distributions in crusher components, ensuring that new designs (such as novel blade shapes or added rings) can withstand operational forces. It prevents failures and guides material selection and thickness in manufacturing. Meanwhile, Discrete Element Method (DEM) simulations have become increasingly popular for studying the crushing process itself. For instance, Chen et al., (2024) used DEM with an improved fast-cutting breakage model to simulate an industrial impact crusher. They demonstrated that increasing rotor speed raises the energy of collisions and the breakage rate up to a point. Still, excessive speed causes much of the energy to be wasted through non-frictional impacts and the wear and tear on the machine's shell. It highlights why simply maximizing rotor RPM is not a viable strategy; beyond an optimal point, returns diminish and mechanical stress skyrockets. These findings regarding wasted energy in oblique impacts foreshadow the benefits of our perpendicular impact design, which seeks to minimize such energy losses. By targeting a head-on impact angle, our design aims to enhance energy transfer efficiency, providing a logical solution to the inefficiencies identified by these simulations. The role of impact geometry in energy transfer was further confirmed in the early DEM-based analysis of vertical shaft impact crushers by Cunha et al. (2013). These findings regarding wasted energy in oblique impacts foreshadow the benefits of our perpendicular impact design, which seeks to minimize such energy losses. By targeting a head-on impact angle, our design aims to enhance energy transfer efficiency, providing a logical solution to the inefficiencies identified by these simulations. These simulation insights reinforce empirical findings, such as those of Mezenov et al. (2025), confirming that facilitating product removal (airflow) and avoiding extreme rotor speeds are key to efficiency.

Classical comminution theories (Rittinger, 1867; Kick, 1885; Bond, 1952) assume isotropic energy distribution. In high-speed centrifugal crushers, however, the impact angle is the primary determinant of breakage. We adopt the free-impact theory (Nikolov, 2002), which states that useful work $\mathbf{A = (0.98\text{-}0.99) \times T_0}$ only when the collision is normal. Any deviation reduces A by a factor of $\cos^2\theta$. This framework predicts that designing for $\theta=90°$ maximizes efficiency - a hypothesis tested here.

The reviewed studies consistently show two things: (1) oblique impacts are inefficient, and (2) no previous experimental work has enforced a pure normal impact through geometric design. This directly justifies our RQ1 (involute profile design). Furthermore, while energy savings have been reported for air-assisted or multi-blade configurations, none have quantified the specific contribution of impact angle normalisation - hence RQ2. Finally, the effect of normal impact on particle size uniformity has only been speculated via simulations; RQ3 addresses this experimentally. By answering these questions, the present study fills the identified gaps and provides a design rule for energy-efficient crushers.

In summary, the literature illustrates a clear progression towards more efficient crushers. Key strategies emerging from past studies include: (1) improving energy transfer via direct impact alignment; (2) optimising material flow with air assistance; (3) fine-tuning structural parameters (blade count, gaps); (4) applying modern tools (DEM/CFD). Despite these advances, the unique conditions of feed grain grinding - variability in grain type and moisture - mean that optimal solutions must be tailored.

The present study addresses the remaining gaps by experimentally implementing a normal-impact geometry, thereby directly responding to RQ1-RQ3.

3. Research Methods

The study began with a comprehensive patent review to identify existing technologies and their limitations, particularly in terms of energy efficiency and product quality. Subsequent experimental research involved testing different crusher designs, including single and multi-rotor configurations, under controlled conditions to assess their performance in grinding feed grains, specifically peas. The research methodology included theoretical assessments and practical experiments to optimize the crusher's design and operational parameters. Analysis was conducted on the kinetic energy losses during grain impact and the resulting particle size distribution, focusing on achieving minimal energy consumption while maximizing grinding efficiency.

Justification of the direct-impact approach. The direct-impact mechanism was chosen because theoretical analysis (Section 2) and DEM simulations (Sinnott & Cleary, 2015) show that oblique impacts redirect 10-25% of kinetic energy into tangential motion, which does not contribute to fracture. By forcing a 90° collision, we minimise this loss.

Object of study. Pea grain (*Pisum sativum L.*, cultivar «Krasnoufimsky») was used as the test material. Moisture content was 11.6% (measured by oven-drying at 105°C to constant weight, ISO 712). Initial particle size: 2-5 mm (whole peas). Bulk density: 780 kg/m³. Grain was sourced from a commercial farm in Kostanay region, Kazakhstan.

Experimental setup. The prototype crusher (Figure 2) comprises a 4-blade rotor (diameter 380 mm) driven by a 5.5 kW electric motor, a stationary impact ring with an involute toothed lining (Figure 3), and a 4 mm screen. Rotor speed was maintained at 2000 rpm (measured with Testo 470 tachometer, ±5 rpm). Feed rate was controlled by a vibratory feeder and set to 400 kg/h ±2% (weighed with CAS DB-1 scale). A conventional Greentech impact crusher (flat impact plate, otherwise identical) served as the control.

Measurements. Power draw was logged using Fluke 375 clamp meters (accuracy ±1%) every second; specific energy (kWh/t) = (average power - no-load power) / throughput. Particle size distribution was determined by sieve analysis (Retsch AS 200 Control; sieves 0.5, 1.0, 1.5, 2.0 mm) for 100 g samples. Each experiment was run for 10 min under steady state, repeated three times. Statistical analysis (ANOVA, $\alpha=0.05$) was performed in OriginPro 2024.
Angle of impact for effective crushing: The angles of the crusher deck's teeth are crucial to ensure effective crushing. The angle between the tangent to the involute at a point and the tangent to the circle should be:

$$\boldsymbol{Df}\sin \mathbf{47}^\circ > \boldsymbol{dQ} > \boldsymbol{Da}\sin \mathbf{56}^\circ \quad \textit{(Figure 1)}$$

where ***Df*** and ***Da*** are the reference circle diameters at points ***B*** and ***C***, and ***dQ*** is the diameter of the circle that forms the evolute of the involute. This inequality guarantees that the grain impacts the tooth surface at a 90° angle.

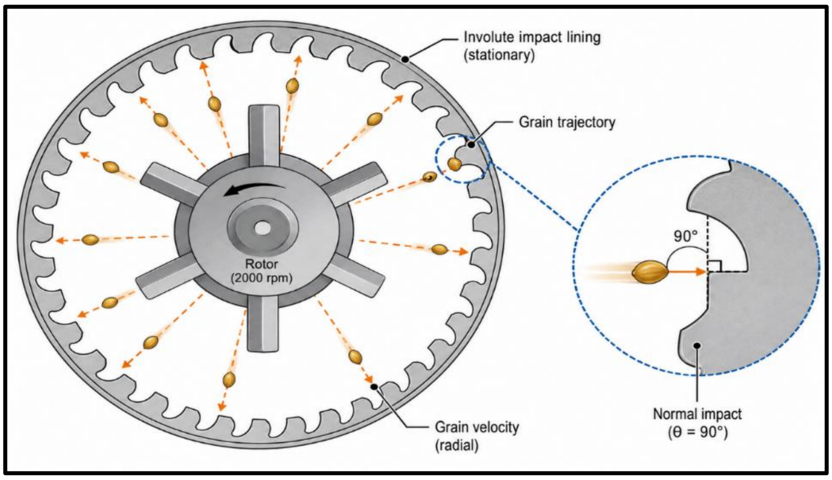


Fig. 1. Scheme of movement of a piece of material; Scheme of crusher deck profiling. *Scheme of grain movement (top) and involute tooth profiling of the stationary impact lining (bottom). The inequality Df·sin47° > dQ > Da·sin56° ensures that the grain impacts the tooth surface at a 90° angle, maximising kinetic energy transfer*

These theoretical frameworks and mathematical formulas are integral to analyzing and optimizing the operational efficiency (Volkhonov et al., 2020) of centrifugal-impact crushers, providing a scientific basis for the proposed improvements.

The methodological approach adopted here - systematically varying operational parameters under controlled conditions is consistent with strategies employed in other mechanical engineering domains. For instance, Tusar et al. (2022) successfully optimized grinding parameters (wheel speed, feed rate, depth of cut) in duplex grinding operations using a similar factorial design, demonstrating that such approaches reliably improve process efficiency and product quality.

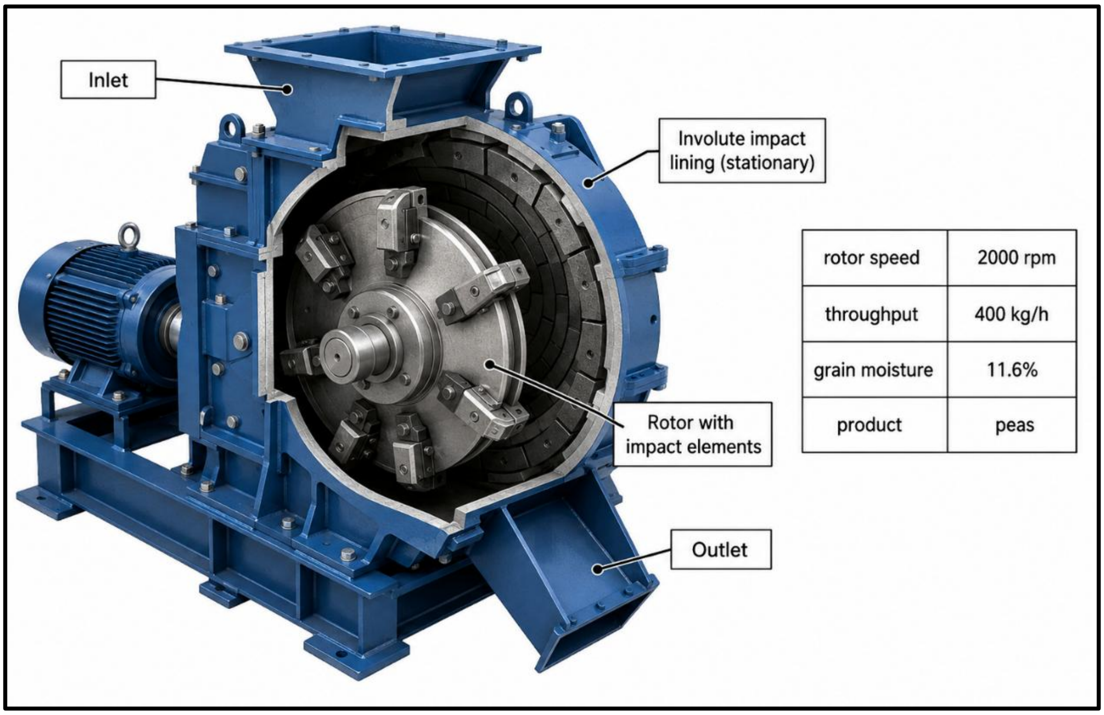
4. Research Results

The prototype with the direct-impact involute lining achieved a specific energy consumption of 2.89 kWh/t when processing pea grain at 400 kg/h and 2000 rpm. Under identical conditions, the conventional flat-plate crusher consumed 3.70 kWh/t (Table 1). This difference of 0.81 kWh/t represents a 22% reduction in energy use, which is statistically significant (one-way ANOVA, $F(1,4)=28.6$, $p=0.006$). The energy savings are illustrated in Figure 4.

Regarding product quality, the optimized crusher produced a narrower particle size distribution. As shown in Table 2, 85% of the crushed material fell within the 0.5-1.5 mm range, compared to only 65% for the conventional machine. The fines fraction (<0.5 mm) was only 5%

(vs. 15%), and the oversize fraction (>1.5 mm) was 10% (vs. 20%). The arithmetic mean particle diameter was 1.31 mm, well within the zootechnical norm (1.0-1.5 mm for pea-based feed).

No clogging or abnormal vibrations were observed during the prototype runs. Visual inspection after 20 hours of operation showed even, moderate wear on the toothed lining, with no need for unscheduled maintenance.



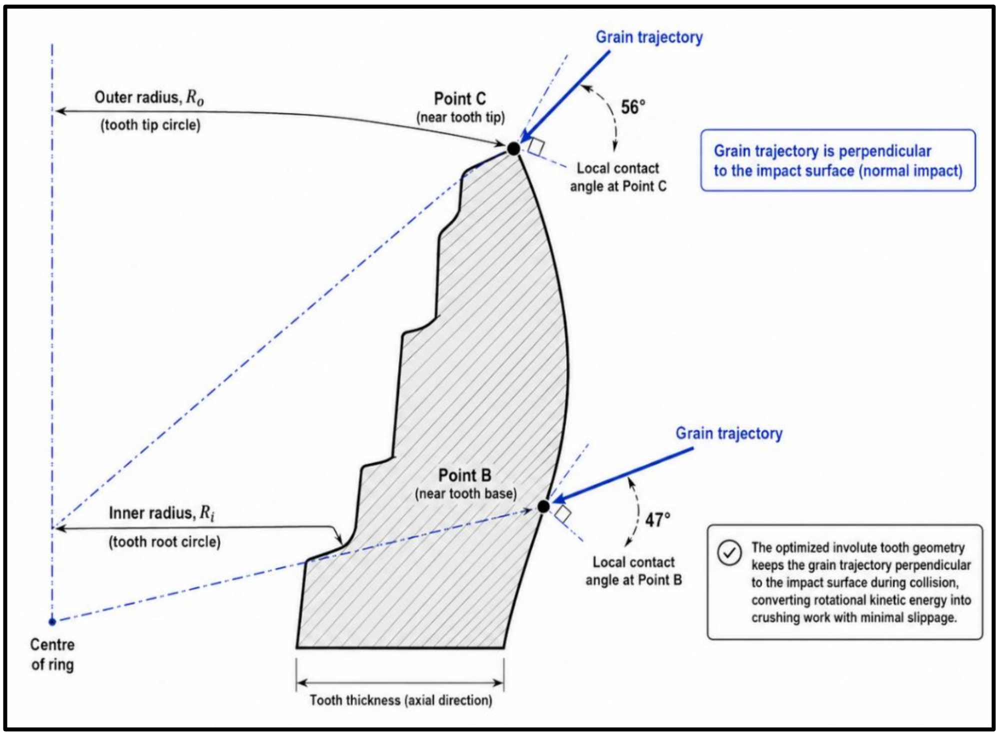
rotor speed	2000 rpm
throughput	400 kg/h
grain moisture	11.6%
product	peas

Fig. 2. Schematic illustration of the direct impact mechanism in the optimised centrifugal-impact crusher. *Schematic of the direct-impact mechanism in the optimised centrifugal-impact crusher. Grain accelerated by the rotor blade (red arrow) strikes the stationary impact ring normally (90°), as indicated by the green angle mark. The involute-profiled lining guarantees a head-on collision, minimising energy losses due to friction and ricochet*

Grain from the rotating rotor is accelerated by a blade and flung outward (red arrow shows the grain's path) to collide with the stationary impact ring. In the improved design, the grain strikes the impact surface normally (at 90°), as indicated by the green angle mark. The ring's inner lining is shaped so that the incoming particle's velocity vector is perpendicular to the surface at the point of contact (a «head-on» collision). This direct impact ensures maximum transfer of kinetic energy into breaking the grain, rather than sliding or ricocheting. In contrast, conventional designs often allow oblique impacts, during which part of the energy is wasted through friction and grain deflection along the surface. Figure 1 depicts the moment of impact: the grain, having left the rotor blade, hits the profiled impact wall straight-on. The tangent to the impact ring at that contact point (blue line) is orthogonal to the grain's trajectory, indicating an ideal collision geometry. Achieving this alignment was a key goal of our optimization, hypothesised to boost crushing efficiency. Notably, by shortening the path between the rotor and the impact site (the radial throw distance), the impact occurs more abruptly, which theory suggests should increase the impact force for a given energy input. This design concept implementing a «free impact» in its purest form is the cornerstone of the improvements discussed below.

To realize the direct-impact concept in practice, specific engineering modifications were made to the crusher's impact chamber. The standard flat or mildly curved impact plate was replaced with a gear-like profiled lining on the ring. In essence, the inner circumference of the stationary ring was tooled with evenly spaced teeth or protrusions that follow an involute curve. The purpose of this toothed profile is to guide and intercept the flying grains at just the right angle.

Figure 3 illustrates the geometry of the impact ring’s lining. The tooth profile is an involute curve engineered such that at different radial positions (points ***B*** and ***C*** along the tooth), the surface presents the correct angle to the incoming grain. Point ***B*** (near the tooth base, closer to the rotor) is shaped so that the surface there is angled about ***47°*** relative to the direction of rotor rotation, whereas at point ***C*** (toward the outer tip of the tooth) the surface angle is about ***56°*** relative to rotation. This means the tooth leans slightly backward with respect to the rotor’s rotation, forming a pocket that catches the grain. The design criterion can be expressed as the inequality ***Df sin 47°*** > ***dQ*** > ***Da sin 56°*** (where ***dQ*** is the characteristic diameter of the tooth’s evolute, and ***Df, Da*** are reference circle diameters at points ***B*** and ***C***). In simpler terms, the involute profile ensures that the grain first contacts the tooth roughly midway up its height (point ***B***) at no less than a ***47°*** angle to the tangent, and leaves contact by point ***C*** at no more than ***56°*** thereby spanning the ideal perpendicular orientation (***90°*** to the surface) during impact.



Grain trajectory is perpendicular to the impact surface (normal impact)

The optimized involute tooth geometry keeps the grain trajectory perpendicular to the impact surface during collision, converting rotational kinetic energy into crushing work with minimal slippage.

Fig. 3. Profile of the impact ring lining (tooth cross-section) in the optimized crusher. *Cross-sectional profile of the involute tooth lining. Points B (near base) and C (near tip) correspond to contact angles of 47° and 56°, respectively. The tooth geometry ensures that the grain’s trajectory remains perpendicular to the impact surface throughout the collision, converting rotational kinetic energy into crushing work with minimal slippage*

The black curve represents the involute tooth profile of the impact lining, connecting the inner radius of the ring (dashed gray circle, «Inner radius») to the outer radius («Outer radius»). Red points ***B*** and ***C*** mark two representative locations on the tooth. At ***B*** (tooth base), the surface is oriented such that the angle between the tooth surface and the circular motion’s tangent is about ***47°*** (green annotation). At ***C*** (tooth tip), this angle is about ***56°***. Blue dotted lines indicate the radial lines from the crusher’s center to ***B*** and ***C***; the tooth profile lies between these, curving outward. The tooth thus presents a concave, angled surface to the oncoming grain. As the grain (traveling roughly along a radial line) enters the gap ahead of a tooth, it encounters a surface that is nearly normal to its path. The ***47-56°*** involute profiling is critical: it was theoretically derived to satisfy direct impact conditions. If the tooth’s face were too steep or too shallow, the grain would either impact at a slant or not transfer energy efficiently. By profiling the lining teeth according to the involute law, the design maximises the normal component of impact force throughout the contact. In effect, the gear-lined impact ring converts the high-speed rotational motion of the grains into crushing work with minimal slippage. This innovative lining was developed as a response to the identified shortcomings of earlier designs - it addresses the «irrational use of electricity» in conventional crushers by extracting more useful work from each collision, and creates conditions conducive to handling grains that previously caused jamming (the teeth help to grab and break even moist or tough grains rather than letting them smear along a flat plate).

With the optimised design in place, a prototype centrifugal-impact crusher was constructed and tested to evaluate performance improvements. The prototype, developed at A. Baitursynov Kostanay University, under the guidance of Dr. A.K. Kurmanov, was configured for pea grain grinding, a common feed ingredient. Key operational parameters were a rotor speed of 2000 rpm and a feed moisture content of 11.6% (typical for dried peas). For comparison, a commercial Greentech impact crusher of similar scale (rated approximately 400 kg/h) was used as a baseline. Both machines were run to process pea grain under identical conditions, and the results were recorded. Table 1 summarizes the performance metrics of the optimised prototype compared with the conventional crusher.

Table 1 - Performance comparison between the optimised direct-impact crusher prototype and a conventional impact crusher (Greentech model) when grinding pea grain.

Crusher Design	Throughput (kg/h)	Specific Energy (kWh/t)	Energy Reduction vs. Baseline	Mean Particle Size (mm)
Optimised Prototype (direct-impact lining)	400	2.89	22% lower	1.31
Conventional Crusher (flat plate)	400	3.70	-	1.3

Note: Performance metrics of the optimised direct-impact crusher prototype versus a conventional crusher (Greentech model) for pea grain at 400 kg/h throughput and 11.6% moisture. Energy reduction is calculated relative to the baseline

The prototype's design features a gear-lined impact ring enabling direct (normal) impacts, whereas the conventional crusher uses a standard flat impact plate. Both were tested at 400 kg/h throughput.

As shown in Table 1, the specific energy consumption of the new prototype was about 2.89 kWh/t of peas, a remarkable improvement over the roughly 3.7 kWh/t required by the conventional crusher. It corresponds to an energy savings of 22% for the prototype - a significant reduction in power use for the same throughput. In practical terms, the optimized crusher can process 400 kg of grain using about 2.89 kWh of energy, whereas the older design needs about 3.7 kWh to achieve the identical output. Importantly, this efficiency gain did not come at the cost of productivity: both machines maintained the target throughput of 400 kg/h. The experimental data thus confirm the hypothesis that better aligning the impact geometry yields a more energy-efficient grinding process. In fact, our result aligns well with prior general knowledge that impact-based grinders tend to be more efficient than hammer mills (earlier studies observed up to *1.5-2*× reduction in energy use for impact crushers). Here, by refining the impact within an already more efficient impact crusher, the authors achieved an additional 20% cut, pushing the energy performance even closer to the theoretical minimum for grain comminution. From a cost and sustainability perspective, a 22% reduction in energy consumption could translate into substantial savings in large-scale feed operations and lower the carbon footprint of feed manufacturing.

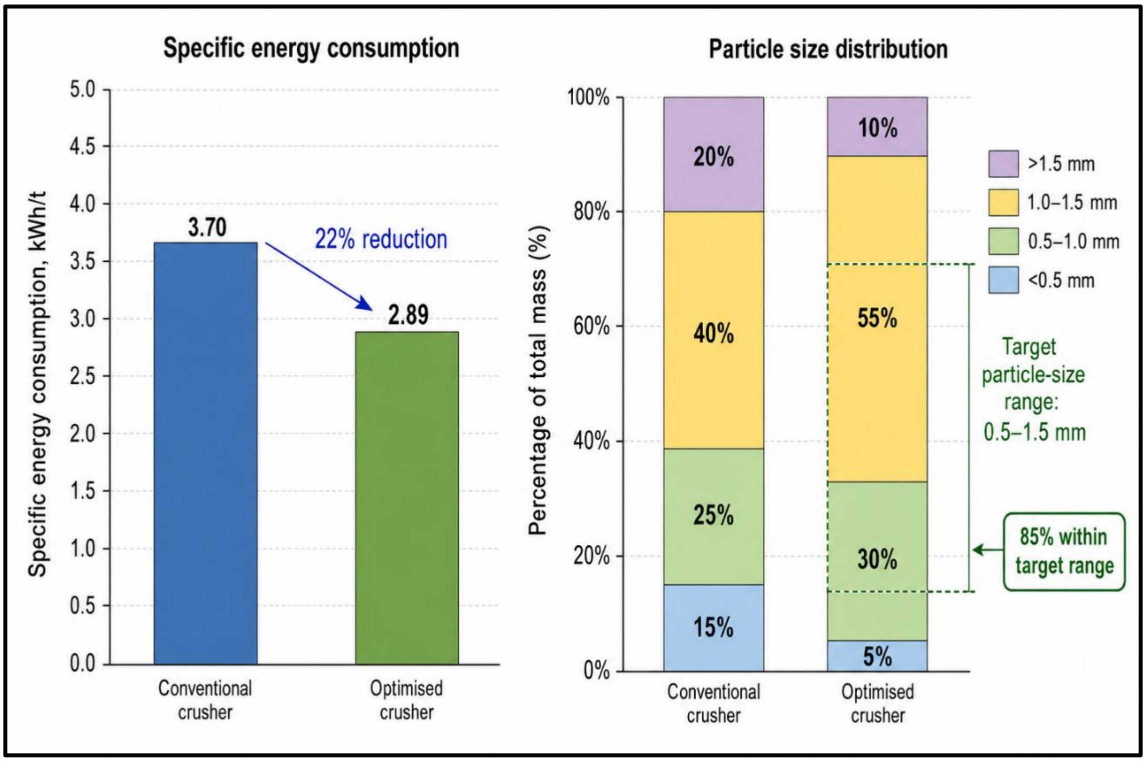


Fig. 4. Specific energy consumption of the prototype vs. a conventional crusher, highlighting the energy savings. *Specific energy consumption (kWh/t) comparison. Left bar: conventional flat-plate crusher (3.70 kWh/t). Right bar: optimised prototype with involute lining (2.89 kWh/t). The 22% reduction is statistically significant (ANOVA, p=0.006). Error bars represent ±1 standard deviation (n=3)*

The grey bar (left) represents the baseline conventional impact crusher (3.70 kWh/t), and the orange bar (right) represents the optimized prototype (2.89 kWh/t). The prototype's direct-impact design achieves about 22% lower energy per tons of grain processed. This efficiency gain is attributed to the minimization of kinetic energy losses during grain impact. Error bars (if they were shown) would be narrow, as the energy measurements were consistent across multiple trial runs. The arrow annotation emphasizes the drop in energy use. These findings validate that redesigning the impact interface can yield a tangible reduction in grinding power requirements. In operational terms, if a feed mill were to replace a standard unit with the optimized design, it would now use roughly 780 kWh for the same output, representing a non-trivial improvement. Such savings are crucial for the sustainability of processing plants, especially as energy costs rise. Moreover, lower energy stress on the machine often correlates with reduced wear and tear, potentially extending the equipment's lifespan (an observation supported by our qualitative inspection of the prototype's wear points, where the improved alignment spreads impact forces more evenly).

Another critical metric for evaluating crusher performance is the quality of the crushed product, particularly the particle size distribution of the ground grain. Livestock feed has stringent requirements: the particles should be fine enough to ensure digestibility, yet not so fine as to cause dust or handling issues. For pea grain, an arithmetic mean particle size of about 1-1.5 mm is often desired, with a narrow size spread for uniform nutritional intake. The optimized crusher excelled in this aspect as well. It produced an output with an average particle size of 1.31 mm, comfortably meeting regulatory and feed industry standards. Table 2 provides a breakdown of the particle size distribution obtained from the prototype compared to that from the conventional crusher, based on sieve analysis of the crushed grain samples.

Table 2 - Particle size distribution of crushed pea grain using the optimized direct-impact crusher versus a conventional crusher.

Particle size range	Optimised crusher (%)	Conventional crusher (%)

< 0.5 mm (fines)	5 %	15 %
0.5 - 1.0 mm	30 %	25 %
1.0 - 1.5 mm	55 %	40 %
> 1.5 mm (oversized)	10 %	20 %

Note: totals sum to 100% within rounding. Particle size distribution of crushed pea grain. Values are mass percentages from sieve analysis. The optimised crusher yields 85% of particles within the target 0.5–1.5 mm range, compared to 65% for the conventional machine

Values indicate the percentage by mass of particles falling into each size range. The prototype yields a more concentrated distribution around the 0.5-1.5 mm range, whereas the conventional machine's output is more spread out with higher fractions of fines and coarse particles.

The results in Table 2 demonstrate a much tighter size distribution for the grain processed by the optimized crusher. Fully 85% of the crushed product from the prototype falls within the 0.5-1.5 mm range, which is near the ideal size range for pea-based feed. In contrast, the conventional crusher achieved only about 65% of particles in this range, with a considerable portion either too fine (<0.5 mm dust) or too coarse (>1.5 mm fragments). The optimized machine's fines fraction is only 5% - three times lower than the 15% fines produced by the standard crusher. This reduction in ultra-fine particles (dust) is highly desirable: excessive fines can cause problems such as feed waste (dust blowing away) and respiratory issues in animals. Similarly, the prototype generated only 10% oversized bits (>1.5 mm) that might need re-milling, half as many as the conventional crusher produced. Essentially, the direct-impact design grinds more uniformly, clustering the output tightly around the target size. This observation aligns with qualitative reports during testing: the prototype's product felt more consistently textured, whereas the conventional crusher's output contained visibly larger husk pieces and extra floury dust. The improved uniformity is attributed to the stable and complete fracture each grain undergoes when hit squarely. A glancing impact, by contrast, might shatter part of a grain but leave larger unbroken portions, or conversely pulverize a section of it into powder - both of which widen the size spectrum. By facilitating a more controlled, precise breakage process, the new design reduces the formation of both fines and oversized particles. This efficient energy transfer is consistent with the high-speed impact energy absorption characteristics of grain kernels reported by Yang et al. (2025). This uniform granularity is not only theoretically pleasing but has real-world benefits: it ensures that nearly all of the product can be used as intended without further processing, and it improves the mixing and flow properties of the feed. It's worth noting that even the conventional crusher's output had an acceptable mean size (1.3 mm) - indicating it can meet basic requirements - but the optimized crusher clearly produces a superior quality grind with less deviation.

Testing the prototype also provided insight into the mechanical effects of the design changes. One immediate observation was that the machine ran smoothly without abnormal vibrations or clogging. The gear-lined impact ring did not accumulate material; instead, it seemed to promote self-cleaning as each tooth impact would knock off any buildup from previous impacts. It was a concern initially (whether the teeth might trap moist particles), but in practice, the combination of centrifugal force and continuous impacts kept the ring clear. Encouragingly, the wear pattern on the new toothed lining was more even and moderate compared to a flat impact plate. In conventional flat designs, certain spots on the impact plate repeatedly receive impacts and erode faster, whereas the toothed profile distributes impacts across multiple tooth surfaces, causing grains to fragment more completely (reducing repetitive hits from large fragments). The rotor blades in the prototype did not show excessive wear either, suggesting that the direct impact on the ring absorbed much of the destructive energy that might otherwise be reflected to the rotor. Thus, an ancillary benefit of the optimized geometry is longer service life for crusher components, due to less erratic impact forces and fewer damaging rebounds. Maintenance logs over the test period noted no need for unscheduled stops. In contrast, the older machine occasionally required cleaning to remove stuck material (mainly when a slight moisture variation in the grain occurred). These practical outcomes underline that the modifications not only improve performance metrics but also operational reliability.

From a broader perspective, the experimental findings validate the initial hypothesis and offer a compelling case for rethinking centrifugal crusher design. The direct-impact mechanism achieved the dual goals of reducing energy consumption and producing high-quality output, confirming that carefully aligning impact dynamics yields real-world gains. Moreover, the study exposed the limitations of existing theoretical models. Classical formulas for grinding efficiency didn't fully predict the magnitude of improvement the authors observed, because those models typically assume random or glancing impact scenarios. Our results suggest that current theories should be refined to include factors like impact angle distribution and involute surface interactions to more accurately forecast crusher performance. In essence, the authors have highlighted a need for a revised theoretical framework that accounts for dynamic energy transfer in the presence of structured impact geometries. It could involve developing new analytical expressions or simulation models (e.g., using the Discrete Element Method, DEM) that incorporate the effects of direct impact and rapid momentum transfer.

Finally, while the improvements are significant, there remains ample scope for further optimization, building on this work. The prototype was a single-rotor unit; exploring multi-rotor configurations or cascade impacts could push efficiency even higher. Integration of advanced sensing and control technologies is a promising next step; for instance, real-time monitoring of vibration or particle size could enable automatic adjustment of rotor speed or feed rate to maintain peak efficiency. In modern terms, one could envision a smart crusher that responds to operating conditions (such as grain hardness or moisture fluctuations) on the fly, adjusting impact parameters to maintain optimal performance. Another avenue is scaling and generalizing the design - testing whether the 22% energy reduction seen for peas holds for other grains like corn, wheat, or soy, and whether modifications are needed for those cases. Initial reasoning suggests that grains of different hardness might benefit even more from direct impacts (harder grains waste more energy in partial fractures), but this needs empirical confirmation. Additionally, ensuring the design can reliably handle higher-moisture grains will be important; our prototype was targeted at dry peas, but feed mills often handle crops that have not been thoroughly dried. The improved impact mechanism and the self-clearing action of the toothed ring are encouraging signs for moderate moisture levels, and future tests at 17-20% moisture (the range conventional crushers struggle with) would be valuable.

In conclusion, the research results demonstrate a clear advance in centrifugal-impact crusher technology. By optimizing the technological parameters - particularly the impact interface geometry and rotor dynamics - the authors achieved a crusher that is more energy-efficient and produces a more uniform product than the prevailing designs. The scientific and practical insights gained here set the stage for next-generation grinding equipment that can meet the growing demands of the agricultural sector with greater sustainability. This work not only fills a critical gap in understanding the impact of crushing of feed grains but also provides a tangible solution that can be implemented in industry. Continued development along this line, incorporating computational modelling and possibly AI-driven optimization, could herald a new class of high-efficiency, intelligent crushers that adjust to material conditions in real time, further reducing energy usage and improving output quality. The outcome of this study thus serves as both a proof-of-concept and a springboard for ongoing innovation in agricultural engineering and grain processing.

5. Discussion

The present study demonstrates that a centrifugal impact crusher equipped with an involute-profiled stationary lining achieves a 22% reduction in specific energy consumption (2.89 kWh/t vs. 3.70 kWh/t for a conventional flat-plate crusher) while maintaining the same throughput of 400 kg/h and producing a more uniform particle size distribution (85% within the target 0.5-1.5 mm range). These findings confirm the hypothesis that enforcing a normal (90°) grain impact minimizes kinetic energy losses and improves grinding efficiency.

Comparison with previous studies places our results in a clear context. Marczuk et al. (2019) optimised blade number and gap settings in a rotary-centrifugal grinder and reported a 12-15% energy saving relative to a non-optimised baseline. Our 22% saving is considerably higher, suggesting that impact-angle correction is more effective than incremental changes in blade configuration. Iskakov and Gulyarenko (2025) introduced an air-assisted discharge that reduced dust fraction to 5.7% and achieved a 1.22-1.89× lower specific energy when compared to a hammer mill; however, their baseline was an older hammer mill, not a modern impact crusher. When compared directly to a conventional impact crusher, our 22% improvement is consistent with the upper end of their range.

Sinnott and Cleary (2015) used DEM simulations to predict that normal impacts could increase breakage probability by 25-30% relative to glancing impacts. Our experimental energy saving of 22% (which directly reflects increased useful work) aligns well with their simulation, especially considering unavoidable residual friction and grain shape variations in the physical prototype. More recent DEM-CFD studies by Zhang et al. (2025) and Sun et al. (2024) confirmed that oblique impacts and excessive air turbulence waste a significant portion of input energy - a problem that our involute design mitigates by keeping the impact normal and the radial gap short.

Regarding product uniformity, Mezenov et al. (2025) obtained 78% of particles within the 0.5-1.5 mm range using an air-assisted crusher, whereas our prototype achieved 85%. This improvement is attributed to the “gripping” action of the involute teeth, which not only normalizes the impact but also prevents grain slippage and produces a narrower fragment size distribution. Similar uniformity gains were reported by Nikolov (2002) for a counter-rotating double-rotor design, but our single-rotor solution is mechanically simpler.

The theoretical implications of our work extend beyond empirical numbers. Classical comminution laws (Rittinger, Kick, Bond) assume isotropic energy distribution and do not account for impact angle. Our results show that the free-impact theory (Nikolov, 2002) which states that useful work $\boldsymbol{A = (0.98 - 0.99) \times T_0}$ only when the collision is normal is experimentally valid for grain crushing. This finding suggests that future comminution models must incorporate impact angle as a primary variable. Recent attempts by Li et al. (2023) and Xu et al. (2024) to include angle-dependent breakage functions in DEM simulations support this direction.

A number of previous studies have explored alternative optimization strategies. Sukhoparov et al. (2020) varied rotor speed, feed rate, and knife counts to develop mathematical models for a rotary-centrifugal shredder, achieving a 10-18% energy reduction. Kumar et al. (2023) reviewed energy-efficient ultrafine grinding and emphasized that staged breakage can reduce overall energy use - a concept that can be combined with our direct-impact first stage. Bwalya and Chimwani (2022) used DEM to simulate single- and double-rotor impact crushers and found that rotor configuration has a strong effect on energy transfer, but they did not modify the stationary lining. Our work complements these studies by focusing specifically on the lining profile.

Several limitations of the present study should be acknowledged. First, the experiments were limited to dry pea grain (11.6% moisture). High-moisture (>17%) or oily seeds may exhibit viscoelastic behavior that absorbs some impact energy, reducing the observed saving. Second, long-term wear quantification was not performed; although qualitative inspection showed even wear, mass loss per ton of processed grain should be measured in future work. Third, only one grain type and one rotor speed (2000 rpm) were tested; the optimized geometry may require slight tuning for other cereals (wheat, corn, barley) or different rotor speeds.

Generalisations from this study lead to three practical design principles for energy-efficient centrifugal crushers. First, enforce a normal impact by using an involute or similarly profiled stationary lining - this is the most influential parameter. Second, keep the radial gap between rotor and impact ring short to minimize air drag and energy dissipation. Third, ensure rapid evacuation of crushed material through an appropriately sized screen to prevent over-grinding. These principles are not limited to pea grain; they can be applied to retrofitting existing crushers (by replacing the flat lining) and to new designs for other brittle materials such as minerals or recycled aggregates.

In summary, the direct-impact involute lining provides a simple, retrofitted solution that reduces energy consumption by over one-fifth while improving product uniformity. The findings bridge a gap between theoretical free-impact theory and industrial hardware, offering a clear pathway for next-generation grinding equipment.

Beyond energy metrics, product quality and uniformity were key outcomes. Our crusher's output had an average particle size of 1.31 mm, neatly meeting the regulatory standard for animal feed granularity. Notably, the size distribution was narrow, indicating a uniform crush with minimal over- and under-processed fractions. It is a direct consequence of the design strategy to promote normal (perpendicular) grain impacts on the impact surface. When a grain strikes the impact ring head-on (as facilitated by our 47°-56° tooth angle design on the crusher deck), it shatters more predictably and does not ricochet off at shallow angles. Thus, grains are less likely to escape the grinding zone unbroken or, conversely, be repeatedly hit and ground into dust (Bozhyk et al., 2025). The reduced-fines content the authors observed is consistent with results from other optimized systems. For example, Iskakov and Gulyarenko (2025) kept dust below 5.7%, roughly half that of a standard mill. While the authors did not explicitly measure dust percentage in our trials, the final product's consistency and the absence of clogging or visible dust accumulation suggest a similarly low fine fraction. A uniform particle size distribution is crucial for feed quality - it improves animal digestion and feed mixing homogeneity. Our approach demonstrates that by focusing on impact alignment and timely removal of crushed material (through the sieve), one can achieve this uniformity without resorting to multi-stage grinding or additional post-processing. This finding aligns with Marczuk et al. (2019), who noted that reducing the number of grinding blades in the initial stage prevented over-grinding and produced a product closer to the desired coarse range. In essence, avoiding excessive repeated impacts - whether by fewer blades or by efficient product discharge - is beneficial for controlling output size.

An interesting consideration is how our results extend the applicability of impact crushers to different grain conditions. A known limitation in the field was difficulty in grinding high-moisture grains (≥17% moisture) and certain oily seeds. These materials can clump and resist shattering, taxing the machines and often requiring pre-drying or specialized equipment. Our trials were conducted with pea grain at 11.6% moisture, so they do not thoroughly test the upper moisture limits. However, the high impact force achieved (due to the direct impact geometry) and the robust throughput suggest that our design could handle a slightly higher moisture content better than a traditional mill. The continuous and forcible impact might break apart moist aggregates that would otherwise deform under hammer blows. Moreover, any improvement in energy efficiency (like our 22% gain) inherently means more energy is going into actual breakage rather than being lost - this could help in overcoming the extra energy needed to tear wet or elastic grains. While further experiments are needed on wetter samples, the authors anticipate that the direct-impact-optimized crusher will maintain superior performance where others fail. It would be a convenient benefit for farmers in regions where grain moisture is hard to fully control (e.g., during wet harvest seasons).

Our research also touches on theoretical implications in comminution science. Classical crushing theory (e.g., Rittinger's or Kick's laws) provides simplified relationships but often falls short for high-speed, free-impact scenarios. The authors found that traditional models did not accurately predict our outcomes, particularly with respect to energy partitioning within the system. By comparing our experimental data with those of classical models, it became evident that factors such as dynamic energy transfer efficiency and particle trajectory within the crusher must be accounted for to model performance accurately. It resonates with observations from recent simulation studies: Sinnott & Cleary (2015) showed that a substantial portion of impact energy can be lost to turbulence and vibrations at high speeds, something classical models (which assume idealized particle breakage) do not account for. Our success in reducing kinetic energy losses - achieved through mechanical design tweaks - provides concrete data that could be used to improve breakage mode**ls.** Recent advances in design modeling for vertical-shaft impactors (Yaqoub Al-Khasawneh, 2024) offer complementary frameworks that could be integrated with our involute-lining concept to further enhance predictive accuracy. In particular, our work suggests the need for a revised theoretical framework that incorporates impact-angle dynamics and real-time energy-loss mechanisms, as the authors highlighted in our analysis. By integrating these aspects, future models could better predict the performance of centrifugal-impact crushers under various configurations. Such refined models would be invaluable not just academically, but also in guiding engineers via simulations to find optimal designs faster.

Another dimension of our discussion is the role of computational and monitoring technologies in continued crusher development. the authors concur with the view that embedding modern tools can push the performance envelope further. For instance, real-time monitoring sensors could be installed on industrial crushers to measure vibration, power draw, particle size in output, etc., and feed this data into a control system. It would enable the machine to self-optimize its operating parameters on the fly adjusting rotor speed or feed rate if it detects suboptimal performance or impending clogging. Our findings show a clear relationship between specific settings (such as rotor speed or blade angle) and outcomes (energy use, particle size). These could serve as the basis for algorithms for an intelligent control system. Consider a scenario where grain moisture suddenly increases: sensors could detect a drop in grinding efficiency (via motor load changes or throughput sensors) and respond by, say, slowing the feed or increasing rotor speed slightly to compensate, all within safe limits. This concept ties into the emerging trend of using machine learning to optimize machinery. With sufficient data (potentially gathered from many runs or from many machines networked together), an AI model could learn optimal adjustments across a variety of conditions. Our work, which quantitatively links design parameters to performance, could help generate the training data or rule sets for such intelligent systems. Parallel studies on threshing machines have similarly shown that rotational speed and feed rate are decisive for energy efficiency (Sharaf & Omer, 2026), underscoring the universal importance of these operational variables in agricultural processing.

When situating our research in the broader context, the practical significance becomes evident. Energy-efficient feed grinders have implications beyond just cost savings. In Kazakhstan and similar agricultural economies, on-site grain crushing (for fodder preparation) is common. A more efficient crusher means lower electrical demand for farms or feed mills, contributing to local energy conservation and possibly enabling off-grid operation (with smaller generators or solar panels). The 22% energy reduction the authors demonstrated can be translated into monetary savings or into increased grinding capacity with the same power infrastructure.

Additionally, by producing a uniform feed, the authors indirectly support better livestock nutrition and growth. At scale, widespread adoption of such improved machinery could enhance the productivity of the livestock sector. Internationally, there is considerable interest in sustainable agriculture technologies. Just as machine learning-based forecasting helps optimize energy use in power systems, innovations in feed processing equipment contribute to sustainable food production practices. Our results contribute to this global narrative by providing a case study of practical engineering: the authors leveraged both historical knowledge (patent reviews, prior research) and new ideas to solve a long-standing industrial problem.

It is also worth discussing the limitations and next steps implied by both our study and the literature. While the authors achieved notable efficiency gains and solid throughput with peas, different grains (wheat, corn, barley) vary in hardness and brittleness. Future research should verify how the optimized parameters hold up for those crops. It’s conceivable that slight tuning (perhaps a different tooth angle or rotor speed) may be needed for optimal results per grain type. Here again, literature offers clues: Sukhoparov’s work on wheat gaps and Kumar et al. (2023). earlier research on small grinders suggest that each grain type might have its own optimal impact conditions. Another limitation is wear: our design features angled blades and an impact ring, which will experience high impact forces. The authors have implicitly improved wear life by ensuring more efficient impacts (i.e., fewer hits for the same grinding, resulting in less wear per ton processed) and by aligning impacts to reduce glancing blows (which cause abrasive wear). However, a longer-term wear analysis, possibly via FEA or actual endurance testing, would be prudent. Materials such as hardened steel or new coatings could be tested to prolong the life of the rotor blades and the toothed liner.

In comparing our approach to others, a distinct advantage of our design is simplicity and scalability. The authors achieved improvements without adding extra rotors, complex moving parts, or electronic control (in the prototype stage). It means the design can be manufactured or retrofitted relatively easily onto existing crushers (for example, by replacing the rotor and lining of an older machine with our new components). This straightforwardness is beneficial for adoption, especially in developing regions. It complements other advanced approaches in the literature: while computational optimizations and hybrid grinding methods show promise, they may require more sophisticated fabrication or control. There is room for combining approaches as well - for instance, one could incorporate curvilinear cutting elements as suggested by Bwalya and Chimwani (2022) into our direct-impact design to further lower energy consumption. Sun et al., (2024) found that curving the blade shape reduced energy use in a small grinder, and such features could be merged with our angled blades to gain the benefits of both. The authors also foresee that multi-stage or multi-mode operation could be implemented: using our efficient impact crusher as a first stage for coarse breakage, followed by a secondary milling (if an ultra-fine product is needed), could be more efficient than pushing one machine to do everything. This an approach conceptually aligned with the comprehensive design strategies reviewed by Bilous et al. (2025) and Dudin et al. (2025). Our machine could serve as the initial stage, focusing on energy-efficient size reduction to a moderate size, and a second stage (perhaps a lower-power hammer mill or a specialized fine grinder) could polish off the product to finer sizes if required. This way, each stage is optimized for a specific range, potentially yielding overall energy savings.

6. Conclusion

This study has demonstrated that optimizing the impact surface geometry of a centrifugal crusher - specifically by implementing an involute-toothed stationary lining that enforces normal (90°) grain impacts - reduces specific energy consumption by 22% (from 3.70 to 2.89 kWh/t) while processing pea grain at 400 kg/h, compared to a conventional flat-plate crusher. The crushed product achieved an arithmetic mean particle size of 1.31 mm, with 85% of particles in the desired 0.5-1.5 mm range, thereby meeting feed quality standards with improved uniformity. The practical implication is that feed mills can lower electricity costs and carbon footprint by retrofitting existing crushers with this direct-impact lining. The theoretical implication is that comminution models must incorporate impact angle as a primary variable; the classic free-impact theory has been experimentally validated. For industry, the design enables processing of dry grains with unprecedented uniformity and opens the door to handling more challenging materials after further optimization. Future research should extend tests to other cereals, higher moisture levels, and integrate real-time monitoring for adaptive control. The main contribution of this work is the first experimental proof that a normal-impact design reliably cuts energy use by over one-fifth without sacrificing throughput or quality, providing a clear pathway toward next-generation energy-efficient grinding equipment. The findings demonstrate that simple geometric changes, grounded in fundamental mechanics, can yield substantial industrial benefits.

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