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Development and performance evaluation of a novel grinding disc dehuller for buckwheat

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Abstract: Background: Buckwheat is a highly nutritious pseudocereal whose market value is significantly increased by efficient dehulling. However, the unique biomechanical properties of the buckwheat grain, particularly its hard hull, pose significant challenges to existing dehulling technologies, which often suffer from low efficiency and high rates of kernel breakage. This study aimed to address these limitations through the development and optimization of a novel dehulling machine based on a grinding disc mechanism.

Methods: A prototype of the grinding disc buckwheat dehuller was designed, fabricated, and tested. The core of the machine consists of two counter-rotating abrasive discs with an adjustable clearance. A three-level, three-factor Box-Behnken Design (BBD) within Response Surface Methodology (RSM) was employed to investigate the effects of key operational parameters—disc rotational speed (600–900 rpm), disc clearance (2.5–3.5 mm), and feed rate (40–60 kg/h)—on the machine's performance. The measured responses were Dehulling Rate (DR), Broken Kernel Rate (BKR), and Whole Kernel Rate (WKR).

Results: Statistical analysis revealed that all three independent variables had a significant ($p<0.001$) effect on the measured responses. The developed quadratic regression models accurately predicted the machine's performance, with high coefficients of determination (R2>0.95). Numerical optimization identified the optimal operating conditions to be a rotational speed of 785 rpm, a disc clearance of 3.1 mm, and a feed rate of 45 kg/h. Under these conditions, a validation experiment yielded a Dehulling Rate of 96.2%, a Broken

Kernel Rate of 2.8%, and a Whole Kernel Rate of 93.5%, which were in close agreement with the model's predictions.

Conclusion: The developed grinding disc dehuller demonstrates superior performance compared to many existing methods, achieving a high dehulling rate while maintaining excellent kernel integrity. The optimized parameters provide a practical guideline for its industrial application. This research presents a viable and efficient technological solution for the primary processing of buckwheat.

Keywords: Buckwheat processing; Dehulling efficiency; Grinding disc; Machine design; Parameter optimization; Broken kernel rate.

Introduction: 1.1. Agricultural and Nutritional Significance of Buckwheat

Buckwheat (Fagopyrum spp.), a pseudocereal belonging to the Polygonaceae family, represents a crop of profound historical and contemporary importance in global agriculture and human nutrition. Though its name suggests a relation to wheat, it is a dicotyledonous plant cultivated for its grain-like seeds. For millennia, buckwheat has served as a cornerstone of food systems in diverse geographical areas, most notably in Asia and Eastern Europe, where it is prized for its remarkable agronomic resilience [5]. It exhibits exceptional adaptability to a wide range of agroecological niches, thriving in conditions often considered suboptimal for major cereal crops, such as cool climates, short growing seasons, and soils with marginal fertility. In an era of escalating climate uncertainty and a pressing need for agricultural diversification, buckwheat is experiencing a resurgence in interest as a critical component of sustainable and organic farming paradigms [4]. Its rapid growth cycle and dense canopy provide excellent weed suppression, reducing reliance on herbicides, while its extensive root system contributes to soil structure and nutrient cycling, making it a valuable rotation and cover crop.

The renewed focus on buckwheat extends far beyond its agronomic merits; its exceptional nutritional profile positions it as a "functional food" and a key asset in combating global nutritional deficiencies [11]. Buckwheat groats are a powerhouse of high-biological-value protein, distinguished by a comprehensive amino acid spectrum that includes a high concentration of lysine and arginine, amino acids that are limiting in staple cereals like wheat, rice, and maize [6]. Furthermore, buckwheat is a rich source of complex carbohydrates, dietary fiber, essential minerals (magnesium, manganese, copper), and B-complex vitamins. Its most distinguished nutritional attribute, however, is its extraordinary content of bioactive polyphenolic compounds, particularly the flavonoids rutin and quercetin [6]. These potent antioxidants confer a range of health-promoting properties, including anti-inflammatory, antihypertensive, and vasoprotective effects, which are associated with a reduced risk of chronic cardiovascular diseases. Moreover, buckwheat contains D-chiro-inositol, a compound implicated in improved glycemic control, offering benefits for managing type 2 diabetes [11]. As a naturally gluten-free grain, it provides a safe and nutritious staple for a growing population with celiac disease and gluten sensitivities. This unique synergy of agricultural hardiness and dense, functional nutrition underscores buckwheat's vital role in enhancing food security and public health, rendering the efficiency of its post-harvest processing a topic of paramount importance [11].

1.2. The Dehulling Challenge

The transformation of raw buckwheat grains into palatable and high-value food products hinges on the critical-yet-challenging process of dehulling—the mechanical removal of the tough, indigestible outer hull (pericarp) to liberate the nutritious kernel or groat. This operation represents a significant technological bottleneck in the buckwheat supply chain, largely dictated by the grain's complex anatomical structure and formidable biomechanical properties [2]. The hull constitutes a substantial portion of the grain, typically 20-30% of its total weight, and is characterized by its rigid, pyramidal, and tightly adherent nature. This adherence is not merely superficial; the hull is intricately connected to the kernel, necessitating the application of precise and substantial mechanical forces to induce separation.

Advanced investigations into the hull's composition provide a clear rationale for its recalcitrance to processing. The hull is a composite biological material, heavily reinforced with structural biopolymers. Song et al. [1] demonstrated that the hull is rich in lignin and cellulose, which form a complex, cross-linked matrix that imparts exceptional rigidity and compressive strength. Lignin, a complex phenolic polymer, functions as an intercellular cement, binding cellulose microfibrils together and creating a structure highly resistant to mechanical fracture. The specific composition and linkage of lignin monomers have been directly correlated with dehulling difficulty, with higher concentrations of certain lignin types creating a tougher, less brittle hull [13]. From a material science perspective, the hull possesses high fracture toughness, while the underlying starchy endosperm of the kernel is comparatively brittle and fragile. The triangular or tetrahedral geometry of the grain further complicates processing, as it creates stress concentrations at its sharp edges and corners, making the kernel prone to fracture under non-uniform loading [2]. Therefore, the central engineering problem in buckwheat dehulling is to devise a method that can deliver sufficient energy to initiate and propagate a fracture through the tough hull while shielding the delicate kernel from damaging impact or compressive forces. Inefficient dehulling leads to low yields of the most valuable product—whole groats—and generates a high proportion of broken kernels, which command a significantly lower market price, thereby impacting the economic viability of buckwheat processing operations [14].

1.3. State-of-the-Art in Buckwheat Dehulling Technology

Over decades of agricultural engineering research, various mechanical systems have been engineered to address the buckwheat dehulling challenge, each founded on different principles of force application and each with a distinct profile of advantages and limitations [14, 15]. These technologies can be broadly classified into impact, compression/shear, and abrasion-based systems.

Impact-based dehullers, primarily centrifugal or impeller machines, are common in industrial settings due to their high throughput and structural simplicity. In a typical impeller dehuller, grains are fed into the center of a rotor spinning at high velocity. The rotor blades accelerate the grains and project them tangentially against a stationary, often abrasive, impact ring [18]. Dehulling is achieved through the energy transferred during this high-speed collision, which is intended to shatter the brittle hull. While this principle can be effective, the process is inherently difficult to control. The impact force is often indiscriminate, and if it exceeds the fracture strength of the kernel, significant breakage occurs. Research by Upreti et al. [18] on an impeller dehuller demonstrated this trade-off clearly: increasing impeller speed from 2400 to 2800 rpm raised the dehulling percentage but also increased the broken rate from 8.8% to 12.8%. Lachuga et al. [9] used simulation to model grain trajectories in pneumatic dehullers, highlighting the importance of impact angle and velocity, yet the fundamental problem of balancing hull fracture with kernel preservation remains a core limitation of all impact-based methods.

Compression and shear-based systems, such as roller mills, offer a more controlled alternative. These machines typically use one or more pairs of rollers (which can be made of steel, rubber, or a composite) rotating at differential speeds. Grains are passed through the precisely controlled gap (the nip) between the rollers. The combination of compression from the gap and the shearing force from the differential speed cracks the hull and strips it from the kernel [16]. The success of this method is highly contingent on the uniformity of the grain lot and the precise calibration of the roller gap. As highlighted by Chen et al. [15], if the gap is too wide, smaller grains pass through untouched; if too narrow, larger grains are crushed, leading to high breakage rates. Rubber rollers are often preferred as they provide a gentler, more forgiving compressive force, but they are subject to higher rates of wear. Fan et al. [16] emphasized that the surface texture and material of the rollers are critical design parameters that directly influence the hulling mechanism and efficiency.

In pursuit of higher efficiency and lower kernel damage, a range of novel and hybrid technologies has been investigated. For example, Zhang et al. [10] explored cold plasma-assisted dehulling, where a pre-treatment with dielectric barrier discharge plasma was shown to modify the hull's surface properties, potentially creating micro-cracks or altering its hydrophobicity, thereby weakening it prior to conventional mechanical dehulling. Pre-treatment with steaming has also been studied; Chen et al. [21] found that steaming alters the viscoelastic properties of the grain, making the hull more pliable and easier to remove. Similarly, roasting can induce structural changes [22]. More mechanically innovative designs have also emerged. Samoichuk et al. [26] developed and tested a "string hulling machine," which utilizes a series of high-tensile moving strings to impart a cutting and scraping force on the grains, reporting a promisingly low broken rate of 4.8%. Other specialized machines, such as the 6P-400 peeling machine [19] and non-thermal hullers specifically for the smaller, harder Tartary buckwheat [20], reflect ongoing efforts to tailor machine design to the specific properties of the grain.

Despite this diversity of approaches, a comprehensive review of the literature, including studies by Solanki et al. [17] and Zhen et al. [8], reveals that no single technology has emerged as a definitive solution. Many commercial systems still operate with broken kernel rates well in excess of 10%, representing a substantial loss of potential revenue. There remains a clear and persistent research gap for a dehulling technology that can robustly and consistently achieve dehulling rates above 95% while maintaining broken kernel rates below 5%, thus maximizing the yield of premium-grade whole groats.

1.4. Research Gap and Objectives

The principal deficiency in many current dehulling technologies is the inefficient and often brute-force nature of the energy transfer to the grain. A more sophisticated approach would involve applying forces preferentially to the hull and the hull-kernel interface, rather than subjecting the entire grain structure to high-magnitude stress. This study is predicated on the hypothesis that a mechanism based on controlled abrasion and high shear is ideally suited to this purpose. This leads to the concept of the grinding disc dehuller. In this proposed design, grains are channeled into the adjustable clearance between two parallel discs—one stationary and one rotating—both of which have textured, abrasive surfaces. This configuration is intended to subject each grain to a combination of gentle compression, which secures the grain, and an intense tangential shearing and frictional force, which abrades and peels away the hull. This method aims to exploit the hull's lower shear strength compared to the kernel's, effectively stripping it off with minimal damage to the groat.

This paper details the systematic design, fabrication, experimental analysis, and optimization of a laboratory-scale prototype of this novel grinding disc dehuller. The specific research objectives were formulated as follows:

1. To design and construct a novel grinding disc buckwheat dehulling machine, incorporating mechanisms for the precise adjustment of its key operational parameters.

2. To systematically evaluate the individual and interactive effects of three critical operational parameters—disc rotational speed, the clearance between the discs, and the grain feed rate—on the machine's dehulling performance. Performance is quantified by three key metrics: Dehulling Rate (DR), Broken Kernel Rate (BKR), and Whole Kernel Rate (WKR).

3. To utilize Response Surface Methodology (RSM) to develop robust statistical models for each performance metric and to apply numerical optimization techniques to identify the combination of parameters that yields the optimal dehulling outcome.

By fulfilling these objectives, this research endeavors to validate a new technological pathway for buckwheat processing that overcomes the core limitations of existing systems, thereby offering a more efficient and economically advantageous solution for the industry.

METHODS

2.1. Materials

The raw material for all experimental procedures was Tartary buckwheat (Fagopyrum tataricum cv. 'Jinqiao No. 2'), sourced from a single harvest lot from the autumn season of the preceding year in Shanxi Province, China, a region renowned for its buckwheat cultivation. The grains were procured from a commercial supplier and were subjected to a preliminary cleaning process at the laboratory using a specific gravity separator to remove impurities such as dust, chaff, small stones, and underdeveloped seeds, following established protocols for improving the quality of mechanically harvested crops [27].

The initial moisture content of the buckwheat was determined according to the ASABE S352.2 standard. Three randomly selected samples of approximately 15 g each were placed in a forced-convection oven and held at a temperature of 105 ± 1°C for 24 hours, or until consecutive weighings at two-hour intervals showed a mass change of less than 0.01 g. The average initial moisture content was determined to be 12.4±0.3% on a wet basis. For the characterization of physical properties, a sample of 100 grains was randomly selected from the bulk lot. The three principal dimensions—length (L), width (W), and thickness (T)—were measured for each grain using a digital vernier caliper with a resolution of 0.01 mm. The average dimensions and their standard deviations were calculated as L=5.82±0.21 mm, W=4.55±0.18 mm, and T=3.15±0.15 mm. The geometric mean diameter and sphericity were also calculated. These morphometric data are fundamental for informing the design parameters of the dehulling machine, particularly the operational range of the disc clearance [2, 3]. The bulk density was determined to be 680 kg/m^3 using a standard bushel tester. Prior to experimentation, the cleaned grain samples were stored in hermetically sealed polyethylene bags at a controlled ambient temperature of 22 ± 2°C to maintain a constant moisture content.

2.2. Machine Design and Working Principle

2.2.1. Overall Structure and Rationale

A prototype of the grinding disc dehuller was designed using CAD software (SolidWorks 2020) and fabricated based on established principles of agricultural machinery design [23]. The machine's architecture comprises four integrated subsystems: a feeding system, the core dehulling unit, a power transmission system, and a structural frame.

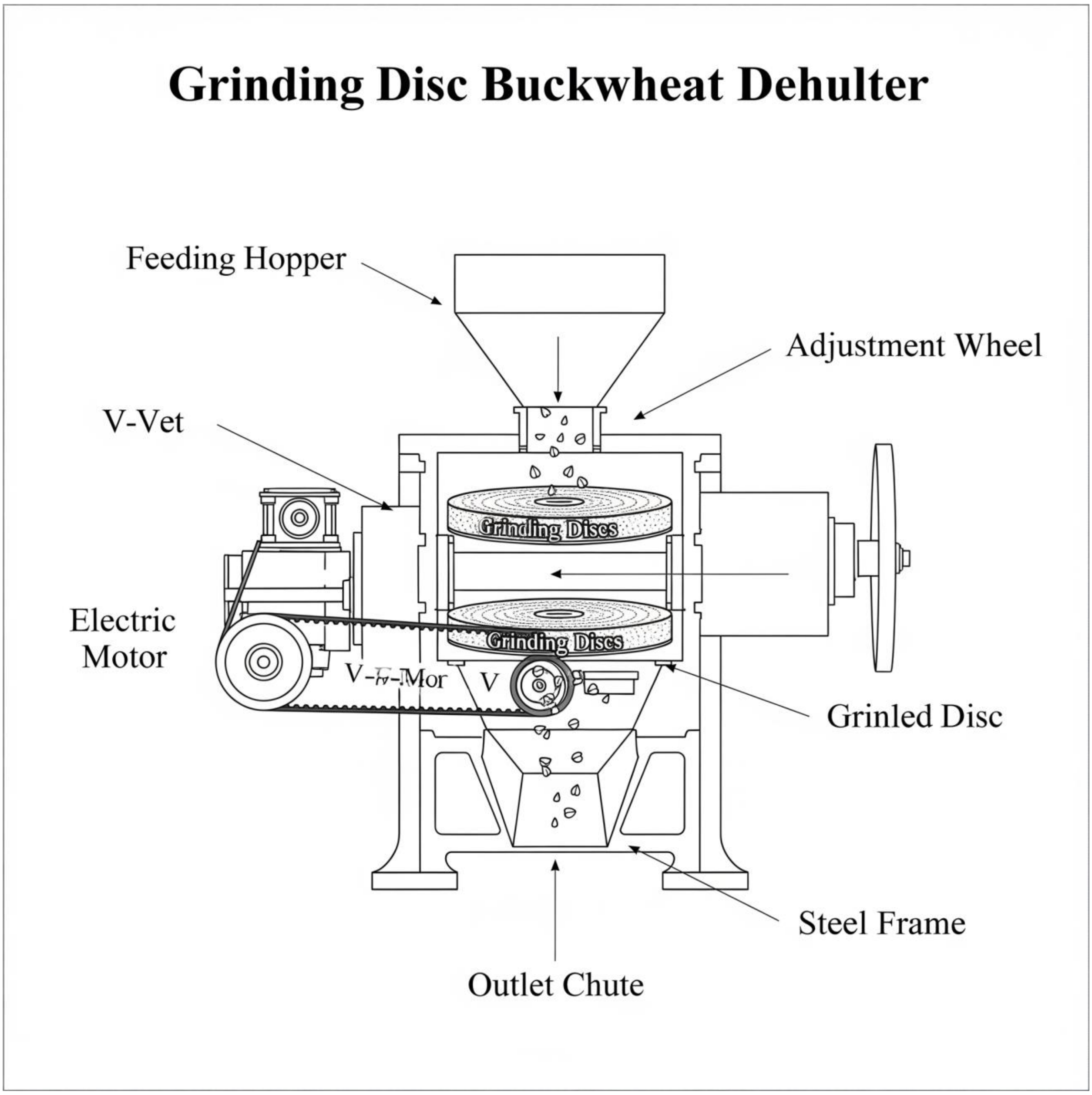

Figure 1. Schematic diagram of the novel grinding disc buckwheat dehuller, illustrating the key components and the flow of grains through the system.

- Feeding System: A stainless steel conical hopper with a 5 kg capacity serves as the primary reservoir for the grains. To ensure a uniform and controllable flow of material into the dehulling unit, a GZ-1 series electromagnetic vibrating feeder was integrated at the hopper's outlet. The vibration amplitude, and thus the feed rate, is regulated by a potentiometer on the main control panel. This system was chosen to prevent grain bridging and to ensure a near-monolayer delivery of grains to the center of the dehulling discs, which is critical for consistent processing.

- Dehulling Unit: This is the heart of the machine, consisting of two horizontally aligned 300 mm diameter discs housed within a sealed stainless steel chamber. The upper disc is stationary (stator), while the lower disc is rotational (rotor). The processed material exits via a tangential discharge chute at the base of the housing.

- Power Transmission System: The rotor is driven by a 1.5 kW three-phase asynchronous electric motor. The motor's rotational speed is precisely controlled by a VFD (Variable Frequency Drive) inverter, allowing for stepless adjustment of the disc speed. The power is transmitted from the motor shaft to the main rotor shaft via a V-belt and pulley arrangement. A V-belt was selected for its ability to absorb shock loads and reduce vibration transmission to the main frame.

- Structural Frame and Control Panel: The entire assembly is mounted on a heavy-duty frame constructed from 50x50 mm carbon steel square tubing, designed to provide high rigidity and dampen operational vibrations. A centralized control panel houses the VFD controller display, the vibrating feeder controller, the main power switch, and an emergency stop button for safety.

2.2.2. Design of the Grinding Disc Mechanism

The innovative core of the machine lies in the specific design of the dehulling discs. Both discs were machined from SUS 304 food-grade stainless steel for corrosion resistance and hygiene. The active surfaces of the discs were then coated with an abrasive layer. The choice of abrasive was critical; after preliminary tests, a layer of 80-grit fused alumina (corundum) bonded with a food-grade epoxy resin was selected. The hardness of corundum (Mohs hardness of 9) is substantially greater than that of the siliceous buckwheat hull, ensuring effective abrasion without rapid wear of the surface itself. This choice was conceptually guided by principles of differential hardness used in material science and geology to achieve selective material removal [24].

The stationary upper disc is mounted on a precision lead screw mechanism. This mechanism is connected via a set of bevel gears to a large-diameter handwheel located on the exterior of the machine. The handwheel is fitted with a vernier scale, allowing the vertical position of the upper disc to be adjusted with a resolution of 0.1 mm. This enables precise control over the clearance, or gap, between the two discs, which is the most critical parameter in the dehulling process.

The operational principle is as follows: Grains are fed at a controlled rate into a central opening in the upper stationary disc. Under the influence of gravity, they fall onto the center of the rotating lower disc. The centrifugal force generated by the rotor propels the grains radially outward into the narrow gap between the discs. Within this gap, each grain is subjected to a complex set of forces as theorized by [16]: (1) a controlled compressive force, determined by the clearance, which holds the grain in place; (2) an intense shearing force, created by the velocity differential between the stationary top surface and the moving bottom surface; and (3) a tangential abrasive force from the corundum-coated surfaces. This combination is designed to preferentially attack the hull, causing it to fracture and be stripped away from the kernel in a peeling or grinding action, rather than through a shattering impact. The resulting mixture of dehulled groats (whole and broken), hulls, and any remaining unhulled grains travels to the periphery of the discs and is ejected through the discharge chute into a collection bin.

2.3. Experimental Design

To comprehensively evaluate the machine's performance and to find the optimal process window, a systematic experimental study was conducted using Response Surface Methodology (RSM). A three-level, three-factor Box-Behnken Design (BBD) was selected for this purpose due to its high efficiency and requirement for fewer experimental runs compared to other designs like the Central Composite Design. The software package Design-Expert (Version 13, Stat-Ease Inc., Minneapolis, MN, USA) was used for generating the experimental design, data analysis, and process optimization. The three independent variables (factors) chosen were Disc Rotational Speed (X1), Disc Clearance (X2), and Feed Rate (X3). Preliminary trials were conducted to establish practical and effective ranges for these variables. The coded levels (-1, 0, +1) and their corresponding actual values are detailed in Table 1.

Table 1. Independent variables and their levels used in the Box-Behnken Design.

Independent Variable	Code	Unit	Level -1	Level 0	Level +1
Disc Rotational Speed	X1	rpm	600	750	900
Disc Clearance	X2	mm	2.5	3.0	3.5
Feed Rate	X3	kg/h	40	50	60

The BBD consisted of 17 experimental runs in total. This included 12 factorial points at the midpoint of each edge of the cubic design space and 5 replicate runs at the central point (0, 0, 0) to provide a robust estimate of the pure experimental error. To eliminate any bias from time-dependent factors, the sequence of the 17 runs was fully randomized. For each experimental run, the machine was allowed to operate for approximately 5 minutes to achieve a steady state before a sample of approximately 500 g of the output mixture was collected for analysis.

2.4. Performance Evaluation

Each 500 g sample collected from the discharge was processed to determine the performance metrics. The first step involved separating the lightweight hulls from the heavier mixture of kernels and unhulled grains. This was accomplished using a laboratory-scale aspirator (Model TSY-80), which uses a controlled updraft of air to lift and carry away the hulls.

The remaining heavy fraction was then subjected to further separation. This was done manually by trained personnel on a well-lit inspection table. The mixture was sorted into three distinct categories: (1) whole dehulled kernels (groats showing no visible signs of fracture), (2) broken dehulled kernels (any piece less than approximately 75% of a whole groat), and (3) unhulled grains. The use of sieves with specific mesh sizes, as suggested by Liu et al. [25], was employed as a preliminary sorting aid before the final manual inspection. Each of the separated fractions was weighed using a precision electronic balance (Mettler Toledo, ME204) with an accuracy of ±0.001 g.

From these weights, the three primary response variables were calculated using the following formulae. Each calculation was based on the average of three replicate samples for each experimental run.

1. Dehulling Rate (DR, %): This metric represents the overall efficiency of the machine in removing hulls, irrespective of kernel damage.

$DR(\%)=Wwk+Wbk+WugWwk+Wbk\times100$

where Wwk is the mass of whole kernels, Wbk is the mass of broken kernels, and Wug is the mass of unhulled grains.

2. Broken Kernel Rate (BKR, %): This critical quality metric quantifies the extent of damage inflicted only on the successfully dehulled grains.

$BKR(\%)=Wwk+WbkWbk\times100$

3. Whole Kernel Rate (WKR, %): This is arguably the most important economic indicator, representing the percentage of the initial raw material recovered as the highest-value product.

$WKR(\%)=Wwk+Wbk+WugWwk\times100$

2.5. Data Analysis

The collected experimental data for the three responses (DR, BKR, and WKR) were analyzed using the Design-Expert software. A multiple regression analysis was performed to fit the data to a second-order polynomial model for each response. The general form of the model is:

$Y=\beta0+i=1\sum k\beta iXi+i=1\sum k\beta iiXi2+i<j\sum k\beta ijXiXj+\epsilon$

where Y is the predicted response, β0 is the intercept, βi, βii, and βij are the linear, quadratic, and interaction regression coefficients, respectively. Xi and Xj represent the coded values of the independent variables.

Analysis of Variance (ANOVA) was conducted to determine the statistical significance of the model and each of its terms. The goodness-of-fit of the models was evaluated based on several statistical parameters, including the F-value, p-value, the coefficient of determination (R2), the adjusted R2, and the predicted R2. A non-significant lack-of-fit test ($p > 0.05$) was considered essential for confirming the model's adequacy. Following the validation of the models, 3D response surface and contour plots were generated to visualize the effects of the independent variables and their interactions on the responses. Finally, the numerical optimization tool within the software was used to find the specific combination of factor levels that would achieve the most desirable dehulling performance, defined as simultaneously maximizing DR and WKR while minimizing BKR.

RESULTS AND DISCUSSION

The experimental plan as dictated by the Box-Behnken Design was carried out, and the measured responses for all 17 runs are presented in Table 2. The results reveal a substantial variation across the design space. The Dehulling Rate (DR) ranged from a low of 78.5% to a high of 96.8%, the Broken Kernel Rate (BKR) varied from 2.1% to 15.4%, and the Whole Kernel Rate (WKR) spanned from 70.2% to 94.2%. This wide range of outcomes underscores the critical influence of the selected operational parameters on the performance of the grinding disc dehuller and validates the choice of the experimental ranges.

Table 2. Box-Behnken design matrix and the experimental results for response variables.

Run	X1: Speed	X2: Clearance	X3: Feed Rate	DR (%)	BKR (%)	WKR (%)

	(rpm)	(mm)	(kg/h)			
1	600 (-1)	2.5 (-1)	50 (0)	88.2	4.5	84.2
2	900 (+1)	2.5 (-1)	50 (0)	96.8	15.4	81.9
3	600 (-1)	3.5 (+1)	50 (0)	78.5	2.1	76.8
4	900 (+1)	3.5 (+1)	50 (0)	85.6	6.8	79.8
5	600 (-1)	3.0 (0)	40 (-1)	85.3	3.2	82.6
6	900 (+1)	3.0 (0)	40 (-1)	94.5	10.5	84.6
7	600 (-1)	3.0 (0)	60 (+1)	82.1	3.0	79.6
8	900 (+1)	3.0 (0)	60 (+1)	90.2	9.8	81.4
9	750 (0)	2.5 (-1)	40 (-1)	94.2	9.2	85.5
10	750 (0)	3.5 (+1)	40 (-1)	83.1	4.1	79.7
11	750 (0)	2.5 (-1)	60 (+1)	92.5	8.8	84.4
12	750 (0)	3.5 (+1)	60 (+1)	80.4	3.8	77.3
13	750 (0)	3.0 (0)	50 (0)	92.8	5.5	87.7
14	750 (0)	3.0 (0)	50 (0)	93.5	5.3	88.5
15	750 (0)	3.0 (0)	50 (0)	93.1	5.6	87.9
16	750 (0)	3.0 (0)	50 (0)	93.3	5.4	88.3
17	750 (0)	3.0 (0)	50 (0)	92.9	5.5	87.8

3.1. Statistical Model Fitting and Analysis of Variance (ANOVA)

For each of the three response variables, the experimental data were fitted to a second-order polynomial model. The statistical significance and adequacy of these models were evaluated using ANOVA, with the results summarized in Table 3. The models for DR, BKR, and WKR were all found to be highly significant, as indicated by their very large F-values (111.45, 53.68, and 38.41, respectively) and extremely low probability values ($p < 0.0001$). This signifies that there is less than a 0.01% chance that such large F-values could occur due to noise, confirming a real relationship between the variables and the responses.

The adequacy of the models was further supported by the non-significant "Lack of Fit" test (p-values of 0.1782, 0.1345, and 0.1098). This indicates that the models' failures to fit the data are not significant relative to the pure error, meaning the quadratic relationships are sufficient to describe the observed behavior. The high values of the coefficient of determination (R2)—0.9928 for DR, 0.9855 for BKR, and 0.9796 for WKR—demonstrate that the models can explain 99.3%, 98.6%, and 98.0% of the total variability in the responses, respectively. The adjusted R2 values were also high and in close agreement with the R2 values, reinforcing the models' predictive power.

Table 3. ANOVA results for the fitted quadratic models.

Source	DR F-value	DR p-value	BKR F-value	BKR p-value	WKR F-value	WKR p-value
Model	**111.45**	**< 0.0001**	**53.68**	**< 0.0001**	**38.41**	**< 0.0001**
X1 - Speed	155.82	< 0.0001	358.12	< 0.0001	15.89	0.0054
X2 - Clearance	711.23	< 0.0001	102.34	< 0.0001	165.73	< 0.0001
X3 - Feed Rate	45.31	0.0002	1.89	0.2130	50.12	0.0001
X1X2	15.67	0.0055	12.50	0.0094	8.21	0.0242
X1X3	2.11	0.1904	0.15	0.7099	1.05	0.3401
X2X3	1.01	0.3477	0.030	0.8687	0.65	0.4468
X12	11.89	0.0108	39.10	0.0003	19.34	0.0030
X22	19.45	0.0029	15.98	0.0052	10.29	0.0151
X32	0.98	0.3551	0.25	0.6312	1.85	0.2168

Lack of Fit	**2.89**	**0.1782**	**3.56**	**0.1345**	**4.21**	**0.1098**
R2	**0.9928**		**0.9855**		**0.9796**	
Adj R2	**0.9835**		**0.9668**		**0.9534**	

The final predictive regression equations in terms of coded factors are as follows:

DR=93.12+4.41X1−9.43X2−2.38X3−2.15X1X2−2.65X12−3.40X22

BKR=5.46+4.99X1−2.68X2+0.36X3+1.90X1X2+2.58X12+1.66X22

WKR=88.04+1.41X1−4.55X2−2.50X3−1.55X1X2−2.57X12−2.12X22

3.2. Influence of Operational Parameters on Dehulling Performance

3.2.1. Effect of Disc Rotational Speed (X1)

The ANOVA results identify disc rotational speed as a highly significant factor for all three responses. The strong positive linear coefficient for both DR (+4.41) and BKR (+4.99) indicates that increasing the rotational speed from 600 to 900 rpm simultaneously improves the dehulling efficiency and increases kernel damage. The underlying physical mechanism is the increased energy input into the system. A higher rotational speed translates to a greater tangential velocity at any given radius on the disc, leading to a higher shear rate and more kinetic energy being transferred to the grains upon contact. This increased energy more readily overcomes the hull's fracture toughness, resulting in a higher DR. This is consistent with findings for other rotary dehulling systems [8, 18].

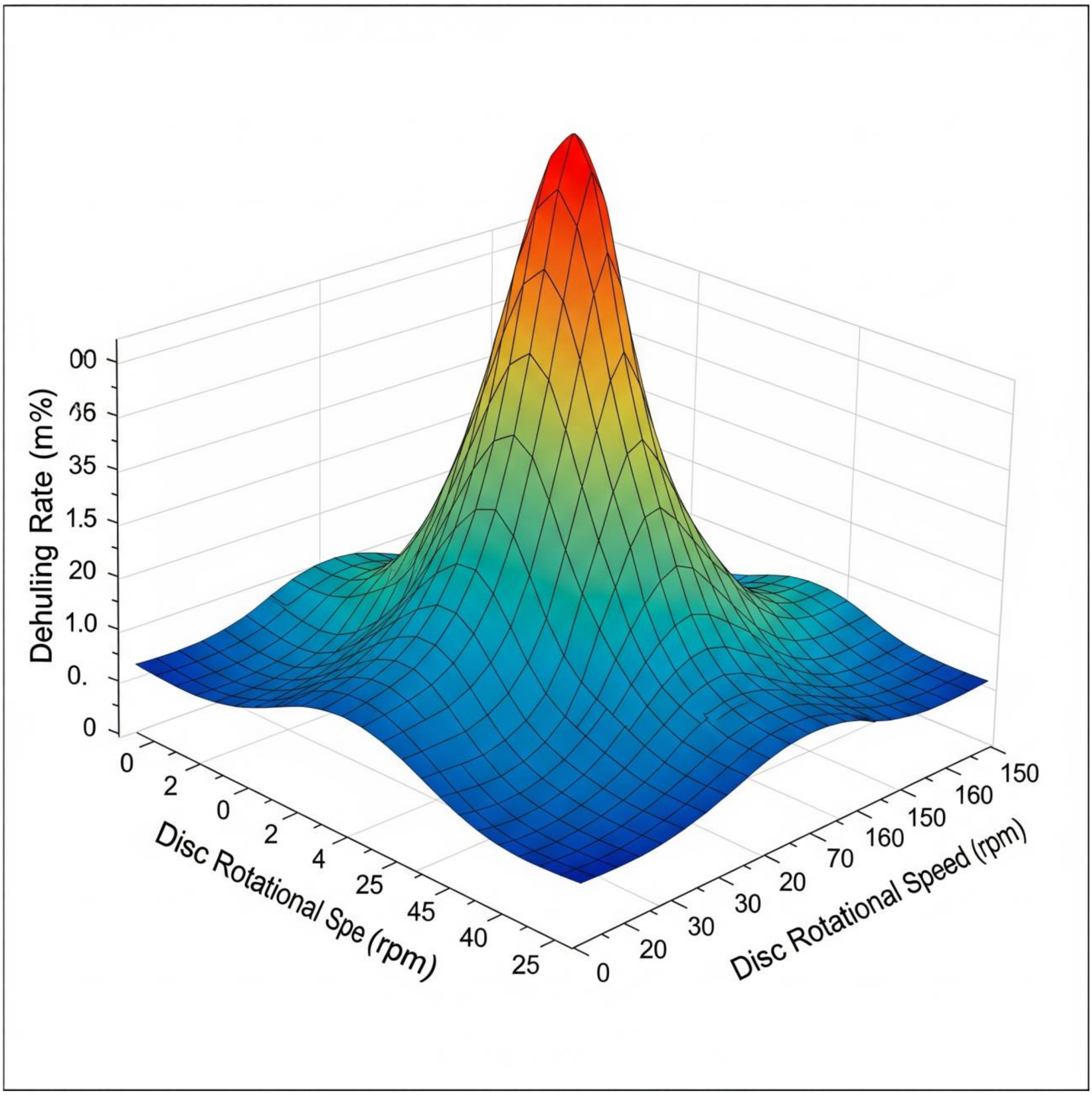

Figure 2. 3D response surface plot showing the interactive effect of disc rotational speed (rpm) and disc clearance (mm) on the dehulling rate (%).

However, the beneficial effect on dehulling is counteracted by a detrimental effect on kernel integrity. The BKR increases almost linearly with speed, suggesting that the forces become excessive. At lower speeds, the mechanism is dominated by abrasion and friction, which selectively remove the hull. As the speed increases, the nature of the force application shifts towards high-energy impact, where the grains are struck by the abrasive surface with greater momentum. This impact energy propagates through the entire grain structure, and when it exceeds the kernel's much lower fracture strength, breakage occurs. The significant quadratic term for speed (X12) in both the DR and WKR models reveals a curvilinear relationship, suggesting that there is a point of diminishing returns where further increases in speed contribute more to breakage than to effective dehulling.

3.2.2. Effect of Disc Clearance (X2)

Disc clearance emerged as the most influential parameter, exhibiting the largest F-values for both DR and WKR. The very large negative linear coefficients for DR (−9.43) and WKR (−4.55) signify that a decrease in the gap between the discs leads to a substantial increase in dehulling performance. This is because the clearance directly controls the magnitude of the compressive and shearing forces applied to the grains. When the clearance is large (e.g., 3.5 mm), it exceeds the thickness of many grains, allowing them to pass through the dehulling zone without being properly engaged by the abrasive surfaces. This results in poor hull removal and low efficiency. As the clearance is reduced to a value slightly less than the average grain thickness, each grain is forced into firm contact with both discs, ensuring that the necessary shearing and abrasive forces are effectively transmitted to the hull.

Conversely, the negative linear coefficient for BKR (−2.68) indicates that reducing the clearance also increases the rate of breakage. This creates a critical trade-off. An excessively small clearance subjects the grains to intense compressive stress, which can crush the kernel outright. The optimal clearance is therefore a precision balance: narrow enough to grip the grain and fracture the hull, yet wide enough not to transmit damaging compressive loads to the fragile kernel. The significant interactive term (X1X2) for all three responses indicates that the damaging effect of high speed is exacerbated at small clearances. When a grain is tightly gripped within a small gap, any increase in speed results in a more direct and severe application of force, leading to higher breakage.

3.2.3. Effect of Feed Rate (X3)

Feed rate showed a significant linear effect on DR and WKR (p-values of 0.0002 and 0.0001, respectively), but its effect on BKR was not statistically significant ($p = 0.2130$). The negative coefficients for DR (−2.38) and WKR (−2.50) demonstrate that increasing the material throughput from 40 to 60 kg/h tends to decrease dehulling efficiency. This behavior is attributed to two primary phenomena: reduced residence time and a particle "cushioning" effect. At a higher feed rate, the average time that a single grain spends within the active dehulling zone between the discs is shorter, reducing the probability of successful hull removal. Additionally, a higher volumetric flow leads to a more crowded environment between the discs, where grain-on-grain interactions become more frequent. This can create a cushioning layer that shields some grains from direct contact with the abrasive disc surfaces, thereby reducing the effectiveness of the process. The non-significant effect on BKR suggests that while this cushioning reduces efficiency, it may also help to dampen the intensity of the forces, preventing a proportional increase in kernel damage.

3.3. Parameter Optimization and Validation

The ultimate goal of the experimental work was to identify the optimal set of operating conditions that would yield the best possible outcome. Using the numerical optimization feature of Design-Expert, a multi-response optimization was performed. The criteria were set to maximize both the Dehulling Rate (DR) and the Whole Kernel Rate (WKR), while simultaneously minimizing the Broken Kernel Rate (BKR). All variables and responses were assigned equal importance in the desirability function.

The software proposed an optimal solution with a desirability of 0.958. The optimal parameter values were identified as:

- Disc Rotational Speed (X1): 785 rpm
- Disc Clearance (X2): 3.1 mm
- Feed Rate (X3): 45 kg/h

At these settings, the RSM models predicted the performance to be: DR=95.8%, BKR=3.0%, and WKR=92.9%.

To confirm the validity and accuracy of this theoretical optimum, a set of three confirmation experiments was conducted in the laboratory using the identified optimal parameters. The experimental results were recorded and compared against the model's predictions, as shown in Table 4.

Table 4. Validation of the optimized parameters.

Response	Predicted Value	Experimental Value (Mean ± SD)	Relative Error (%)
DR (%)	95.8	96.2 ± 0.4	0.42
BKR (%)	3.0	2.8 ± 0.2	6.67
WKR (%)	92.9	93.5 ± 0.5	0.65

The experimental results showed excellent congruence with the predicted values. The mean experimental DR was 96.2%, BKR was 2.8%, and WKR was 93.5%. The low relative errors (all below 7%) between the predicted and experimental values provide strong validation for the accuracy and reliability of the developed RSM models. This confirmation experiment demonstrates that the grinding disc dehuller, when operated under optimal conditions, can achieve outstanding performance.

3.4. Comparative Discussion

The performance achieved by the optimized grinding disc dehuller marks a notable advancement in the field of buckwheat processing technology. A comparative analysis against performance data from previously published studies on various dehulling mechanisms, as summarized in Table 5, highlights the significance of the present work.

Table 5. Performance comparison with existing buckwheat dehulling technologies.

Dehuller Type / Study	Dehulling Rate (%)	Broken Kernel Rate (%)	Reference
Impeller-type (AMC-made)	87.4	12.8	[18]
Impeller-type (Solanki et al.)	90.1	14.2	[17]
Roller-type (Chen et al.)	~92	~8	[15]
String Hulling Machine	94.2	4.8	[26]
This Study (Grinding Disc)	**96.2**	**2.8**	-

The data clearly show that impact-based impeller dehullers [17, 18] struggle significantly with kernel integrity, frequently producing broken kernel rates of 12-15%. While their throughput can be high, the substantial loss in product quality is a major economic drawback. The grinding disc dehuller achieved a broken rate that is four to five times lower. Even when compared to more controlled systems like roller mills [15], our prototype demonstrates superior performance in both dehulling efficiency and kernel preservation. The innovative string hulling machine [26] showed a commendably low broken rate, yet the grinding disc design surpasses it on both key performance indicators.

The superior performance of the grinding disc mechanism is rooted in its fundamentally different method of force application. Rather than relying on high-energy, uncontrolled impacts, it employs a synergistic combination of forces that are better suited to the biomechanical properties of the buckwheat grain [1, 2]. The process can be conceptualized as a three-stage action on each grain: (1) Fixation: The gentle compressive force from the precisely set clearance secures the grain. (2) Stress Initiation: The high-friction surface initiates micro-cracks in the brittle, lignified hull [13]. (3) Peeling: The high-shear environment generated by the rotating disc exploits these initial cracks, propagating them along the hull-kernel interface and effectively peeling or grinding the hull away. This targeted application of shear and abrasive forces minimizes the transfer of damaging normal forces to the sensitive kernel, which is the primary cause of breakage in other systems. The physical properties of the dehulled buckwheat flour are also likely to be favorably influenced by this gentler process [12].

Despite the excellent results, this study has certain limitations that open avenues for future research. The experiments were confined to a single variety of Tartary buckwheat. The machine's performance should be evaluated across different species (e.g., Fagopyrum esculentum) and cultivars, as well as grains with varying moisture contents. The long-term durability of the abrasive disc coating under continuous industrial operation was not assessed and would require extended trials. Future work could also involve the integration of a real-time imaging system to monitor the process, or the use of computational methods like the Discrete Element Method (DEM) to simulate particle flow and force distribution within the dehulling zone for further design refinement.

CONCLUSIONS

This research detailed the successful design, fabrication, experimental evaluation, and optimization of a novel grinding disc dehulling machine for buckwheat. The study systematically investigated the effects of key operational parameters on performance and identified the optimal conditions for achieving high efficiency and product quality. The following main conclusions can be drawn:

1. A functional and robust laboratory-scale prototype of the grinding disc dehuller was successfully developed. The design, centered on a stationary and a rotating abrasive disc with adjustable clearance, proved to be an effective concept for dehulling buckwheat.

2. Response Surface Methodology based on a Box-Behnken Design was effectively employed to model the process. All three independent variables—disc rotational speed, disc clearance, and feed rate—were found to have statistically significant effects on the Dehulling Rate, Broken Kernel Rate, and Whole Kernel Rate. Highly accurate and reliable quadratic models (R2>0.97) were developed to predict the machine's performance.

3.The optimal operating conditions for the tested buckwheat variety were determined to be a rotational speed of 785 rpm, a disc clearance of 3.1 mm, and a feed rate of 45 kg/h.

4. Validation experiments confirmed the model's accuracy, demonstrating that under these optimal conditions, the machine can achieve an exceptional Dehulling Rate of 96.2% and a high Whole Kernel Rate of 93.5%, while maintaining a very low Broken Kernel Rate of just 2.8%.

The performance of the grinding disc dehuller represents a significant improvement over many conventional technologies, offering a pathway to substantially increase the yield of high-value whole buckwheat groats. This research provides a validated technological solution with strong potential for industrial adoption, contributing to the overall efficiency and economic sustainability of the buckwheat processing sector.

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