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The effect of operating parameters on the performance of an innovative garlic clove separating machine

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ABSTRACT

Garlic is an essential crop in Egypt with significant culinary and medicinal value, yet manual clove separation remains laborious and inefficient. This study aimed to develop an innovative garlic clove separating machine. Machine performance was assessed across three parameters: drum speeds ranged between 22 and 41 rpm, moisture content (MC) ranged between 46 and 62%, and clearance settings ranged between 10 and 20 mm. MC emerged as the most critical performance determinant, with optimal separation efficiency at 48–56% MC. Clearance settings significantly influenced quality, where 20 mm clearance maximized capacity while 10 mm enhanced purity, particularly for MC bulbs (<45% MC). Clove damage showed strong MC dependence, with 20 mm clearance minimizing injury in moist bulbs and 10 mm optimal for drier conditions. MC and clearance adjustments proved more impactful. The study identified key trade-offs: higher MC improved throughput but increased damage, whereas tighter clearances boosted purity at the expense of separation completeness. The practical recommendations include processing at 49–54% MC,

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using 10 mm clearance for dry bulbs and 20 mm for wet ones, and adjusting drum speed accordingly (32–41 rpm). These guidelines can improve processing efficiency by 18–22% while reducing damage losses by up to 15%.

KEYWORDS

drum speed, garlic processing, machine performance, mechanized separation, separation efficiency, separating machine

1. INTRODUCTION

Agricultural machinery contributes significantly to productivity, saves labor costs and time, and produces quality, so bringing attention to the latest advances is essential (El Ghobashy et al., 2023). Given the critical contributions of agricultural machinery to productivity and efficiency, it is equally important to consider its role in enhancing the processing—especially the separation process—of crops like garlic, which holds immense value in various sectors, including agriculture, health, and the food industry (Cujbescu et al., 2019). Garlic (*Allium sativum* L.) plants are used as vegetables and spices and are widely considered to have potential bioactive compounds, especially in agriculture, human health, and pharmaceutical applications (Praticò et al., 2018; Yan et al., 2023). Using garlic as an additive in foods may provide inhibition of foodborne pathogens (El-Jakee et al., 2024). Fresh garlic and garlic oil are natural antimicrobial food additives that can help prolong the shelf life of meat products and reduce foodborne pathogens (Sallam et al., 2024). Its health advantages have long been recognized in Greece, Egypt, and China. Furthermore, it was also used by the Romans (Kovarovič et al., 2019). Garlic products are highly requested in the home market, especially for the snack and catering industries, besides being exported to important nations to increase their worldwide market value (Tullo Wako and Haptegebriel, 2024).

The garlic cultivation area in Egypt reached about 48,660 fed, producing 490,417.53 tons (FAOSTAT, 2025). To make processing easier, the cloves are separated from the bulb by shattering them (Mudgal and Sahay, 2009). The material used to plant garlic is garlic cloves. Using wooden tools, the garlic cloves are broken off from the bulb and crushed (Channabasamma, 2014). Frequently, garlic cloves are separated by shearing the bulb between the two palms rather than sacking or hammering with a wooden rod. These procedures are time-consuming, laborious, and can lead to hand harm (Mudgal and Sahay, 2009). Therefore, the manual garlic separation activities highlighted the need for mechanization to boost efficiency and minimize expenses. Designing equipment specialized for separating garlic bulbs will expedite these procedures, saving time and labor. This automation is predicted to promote clove activity and quality consistency, which is necessary for good mechanical planting performance, resulting in better crop yields and lower overall planting costs (Abd ElGawad, 2021; Morad et al., 2020).

Considering the abovementioned concerns, Channabasamma et al. (2016), Mudgal and Sahay (2009) experimented with examining the breaking processes and the impact of rubber materials on the breaking efficiency of a rubber roll garlic bulb separator. The results showed that the shearing stress determines the breaking ratio. They advised bulbs to run between rubber rollers before shattering, which produced a significant effect and shearing force at the apex of the bulb that aided in shattering.

In summary, studies by Channabasamma et al. (2016), Kovarovič et al. (2019), and Mudgal and Sahay (2009) have revealed that there are significant differences in the breaking mechanisms of garlic bulbs and cloves at various roller speeds and feed rates. Our understanding of how garlic bulbs become garlic cloves under various feed rates or roller speeds has benefited from the previous work. Nonetheless, the breaking unit size, feed rates, and roller speeds on the breaking of garlic bulbs in all the aforementioned research were chosen to accord with the qualities of garlic bulbs in several Asian nations. The rubber roll garlic bulb separator primarily comprises two rolls with highly elastic rubber coverings; garlic bulbs are struck and sheared within the breaking process. Based on the force required to extract the garlic cloves from the entire garlic bulb 40.7 N—rubber deforms more during the breaking procedure than the garlic bulb because it is less rigid than the garlic bulb (Channabasamma et al., 2016).

The performance of the garlic separation machine is critically influenced by three key parameters: moisture content (MC), drum speed, and clearance. These factors collectively determine efficiency and product quality across various applications, from garlic separation to husk cleaning. MC significantly impacts material behaviour during processing. Higher MC (40.5%) increased clove adhesion and damage (18.1%), while lower MC (23.1%) caused brittleness, reducing efficiency. In addition, drum speed directly affects shear and compression forces. In garlic separation, 36 rpm (0.48 m s^{-1} peripheral speed) balanced these forces, achieving 86.6% efficiency and 4.7% damage (Manjunatha et al., 2014). However, lower speeds (0.48 m s^{-1}) reduced loss but compromised efficiency (Abu Ali et al., 2022). Optimal clearance ensures material flow without excessive damage. A 10 mm cylinder-concave gap in garlic separation optimized efficiency (86.6%) and minimized unseparated cloves (4.7%) (Manjunatha et al., 2014). The interaction of these parameters is crucial. For example, combining 36 rpm drum speed, 10 mm clearance, and 27.7% MC in garlic separation yielded peak efficiency (86.6%) and minimal damage (4.7%) (Manjunatha et al., 2014). Optimizing MC, drum speed, and clearance is essential for balancing efficiency and product quality.

Previous research shows that agricultural garlic-separating machines are bulkier, fewer, and more expensive, consuming more energy, based on the cultivar of Chinese garlic in Egypt. To close this gap, it will be necessary to construct an inexpensive and effective garlic bulb-breaking machine in Egypt using supplies from the Egyptian market. This rises with the expansion of Chinese garlic farming for export in Upper Egypt. Hence, this study aimed to develop an innovative garlic clove separating machine, presenting a compact, user-friendly garlic clove separator machine with a novel drum design that meets small farmers' needs, identifies optimal operating parameters for high-quality output, and analyzes the relationship between quality metrics, moisture content, drum speed, and drum-head clearance to steer future improvements.

2. MATERIALS AND METHODS

The garlic bulb breaker machine was developed and tested from September to December 2023 at a private workshop in Al-Khosoos, Cairo. Field experiments were conducted from June to July 2025 at a private farm in Abu Hammad, Sharkia Governorate, while the drying treatments were performed at the Faculty of Agriculture, Zagazig University. Chinese garlic cloves were utilized in this study. The physical characteristics of Chinese garlic cloves are presented according to Abd ElGawad (2021). These measurements were conducted following the guidelines established by Mohsenin (1986), using a sample of 100 cloves.

A three-hundred-kilogram purchase of locally sourced fresh garlic bulbs was grown in the Zagazig area to meet the demands of the upcoming season. The garlic bulbs were then enclosed in polyethylene plastic bags and transferred to the Faculty of Agriculture, Zagazig University, for drying.

2.1. Drying of garlic bulbs

The garlic bulk was divided into three smaller batches, weighing approximately 100 kg. These batches were spread on the surface of the top floor for drying under indirect solar radiation in an open area, simulating the traditional drying method commonly practiced by farmers. Before the commencement of the drying process, three representative samples were collected in the laboratory to determine the initial moisture content (MC). The total mass of each sample was measured at three-day intervals throughout the drying period to monitor and calculate the reduction in MC. The drying process was conducted during May and June 2025. Bulbs were manually pre-sorted bulbs by MC and preconditioned at three levels. The initial average MC across the three samples was 73.02%, with individual values of 65.85%, 72.60%, and 80.60%. Drying continued until the desired target moisture levels were achieved for each sample. These target MCs were 46.5, 55.62, and 62.73%, respectively. Upon reaching the target moisture levels, the samples were stored under controlled room temperature conditions (25 ± 1 °C) until they were used to assess mechanical performance characteristics.

2.2. Machine description

Cloves are separated from garlic bulbs by applying impact and shearing forces (Ibrahim, 2013). A garlic clove separator considered this basis and the engineering characteristics of Chinese garlic varieties in El-Sharkia (Abd ElGawad, 2021). The machine comprises an input hole, rubber rollers mounted on one axis, a blower wheel, two exits for the garlic cloves and the husks, two electric motors, and two driving systems (engine, belt, and pulley). Two holes were created above the roller input hole to insert the garlic bulbs. The rubber rollers have a length of 402 mm and a diameter of 208 mm to generate a shearing impact with the concave to generate cloves. The concave rolls were also covered with an extra layer of rubber padding to prevent the cloves from being damaged.

The blower wheel, with a length of 460 mm, a width of 95 mm, and a diameter of 191 mm, was used to create airflow to clean the debris that fell from the roller. An electric engine (0.75 hp) powered the machine's prime mover with all its components. The belt and pulley system provided power transmission to the roller and blower components. All the above components had appropriate supports and were all mounted to the machine's mainframe. The machine's overall dimensions were 505 × 480 × 1,330 mm (length, width, and height, respectively).

2.2.1. Feed hole and bulb breaking unit. The feed holes have a lid that can be opened easily using an upper handle, as shown in Fig. 1. The separator includes two rollers on the same axis, all in separate rooms, as a dynamic part. The static part was the concave rubber around the

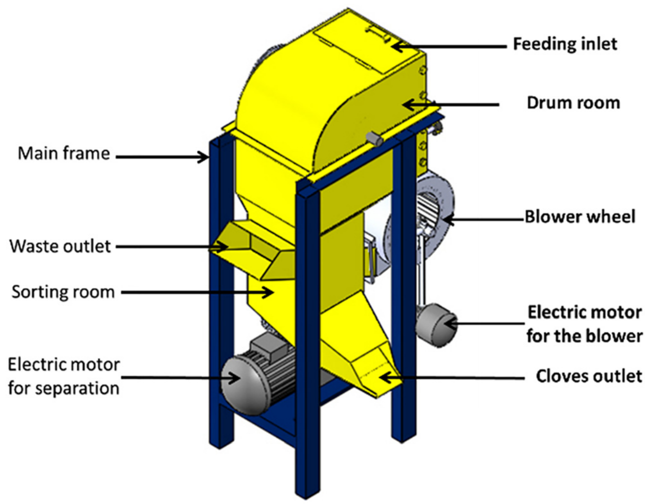

Fig. 1. Garlic bulb breaker components. (Own source)

roller, and that was the outer covering that held the garlic to be processed to a clearance. The clearances between the drums and the concave were designed according to garlic cloves dimensions and controlled by adjustment screws, Fig. 2. The rollers comprised layers of compacted rubber sheets, 25 mm thick, 402 mm length, and 200 mm outside diameter. The rollers were assembled to the main frame via the supports and ball bearings. The separating room was built of 1.5 mm-thick steel sheet metal.

2.2.2. Machine outlets. The outlet for the cloves was configured as a chute, with the end where the materials left the machine at a 45° slope to the horizontal. This slope exceeds the angle of repose of a garlic clove measured at 37.56°. Both exits were provided below a room separating

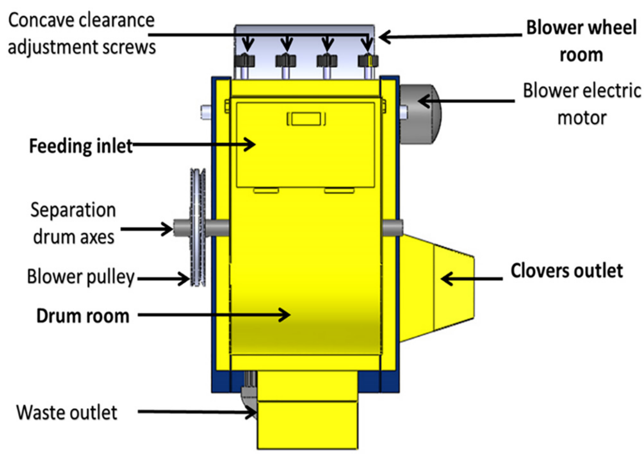

Fig. 2. Assembly of garlic bulb separator. (Own source)

the collection of light components and cloves into two levels. The first level defined the waste material exit on the opposite side of the air fan, which the air current had conveyed and removed the husk and roots from the machine. The rectangular shape of the husk exit was angled upward at the inside end to receive the husks being conveyed by air. The second level was the clove outlet, whereby the cloves left the machine at 45° to the horizontal. The machine's outlets are illustrated in Figs 1 and 2.

2.2.3. Machine main frame. The machine's main frame is made of mild steel angles with 40 × 40 × 6 mm dimensions. It has a length of 505 mm, a width of 465 mm, and a height of 830 mm. The main frame houses the following components: an input hole, a fan, an outtake, two rubber rollers, and an engine mount. The frame also supports and attaches all other machine components (Figs 1 and 3).

2.2.4. Transmitting power system. The garlic bulb breaker is powered by a 0.56 kW (0.75 hp) electric motor on a balanced base connected to the bottom of the mainframe. The blower wheel is powered by a 0.25 hp electric engine on the base attached to the main frame's left edge. Power is transmitted to the rollers and fan via a V-belt and pulley arrangement, with consideration given to achieving the belt tensions, as shown in Fig. 2.

2.2.5. Air blower wheel. The blower is a crucial component in various ventilation systems, providing airflow. The housing includes an air outlet on the internal side to deliver compressed air toward the material that descends directly below the rollers and opens to air on the two ends. The fan is powered by a belt and pulley from the two roller pulleys at a speed of 500 rpm. The air blower wheel unit is shown in Figs 1 and 3.

2.3. Design trial

The trial was conducted using a 54 complete factorial design in a completely randomized design (CRD) with three factors: moisture content, clearance, and drum speed, resulting in 18 treatment combinations that were each replicated three times, leading to 54 experimental runs. These factors were selected based on previous research related to garlic bulb-breaking unit size

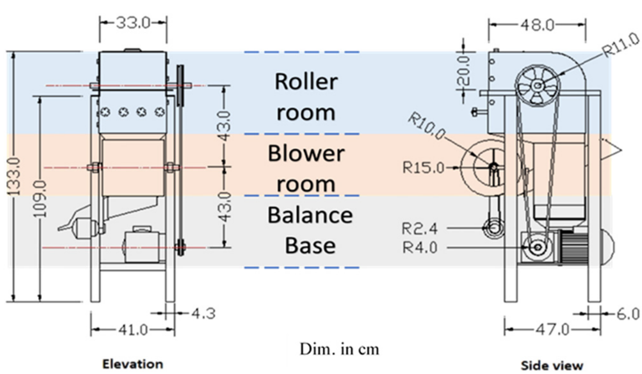

Fig. 3. Views of fan size and components. (Own source)

innovation, as reported by Abd ElGawad (2021), Dress and Ibrahim (2013), Ibrahim (2013), and Mudgal and Sahay (2009). The experiment includes three moisture contents: 46.5, 55.62, and 62.73%; two clearances: 10 (CL-10) and 20 (CL-20) mm; and three drum speeds: 22 (0.28), 33 (0.42), and 41 (0.52) rpm (m s^{-1}). This experimental setup allowed for the evaluation of both main effects and interactions among the factors on the performance of the garlic bulb-breaking unit.

2.4. Machine performance evaluation

Garlic bulb samples were continuously fed into the machine via designated feeding holes, enabling uninterrupted processing across all experimental treatments. The machine separated the bulbs into distinct fractions, including whole single cloves, double cloves, unseparated bulbs, broken cloves, and light materials. Each separated fraction was collected and weighed individually using a digital weighing balance. To ensure reliability and consistency, each experiment was conducted in triplicate, and the data were recorded independently for each trial. The collected fractions were then analyzed to evaluate key performance parameters of the machine: garlic bulb separating efficiency (SE), bulb breaker (machine) capacity (MaC), purity (PU), unseparated bulbs (UB), double cloves (DC), clove damage percentage (CD), fan losses (FL), total losses (TL), and clove germination rate. These performance indicators were assessed following the methodologies described by Channabasamma et al. (2016), allowing for standardized comparison and benchmarking of machine effectiveness (Equations (1)–(8)).

$$E\ (\%) = \frac{Mass\ of\ separated\ cloves\ (S)}{Total\ input\ mass\ (I) - Husk\ mass\ (F)} \times 100 \tag{1}$$

$$MaC(kg/h) = \frac{Mass\ of\ separated\ cloves\ (S) + Non\text{-}separated\ cloves\ (C)}{Processing\ time\ (T)} \tag{2}$$

$$PU(\%) = \left[1 - \left(\frac{Husk\ mass\ (F)}{Total\ input\ mass\ (I)}\right)\right] \times 100 \tag{3}$$

$$UB(\%) = \frac{Mass\ of\ unseparated\ bulbs\ (U)}{I - F} \times 100 \tag{4}$$

$$DC\ (\%) = \frac{Mass\ of\ double\ cloves\ (D)}{I - F} \times 100 \tag{5}$$

$$CD\ (\%) = \frac{Mass\ of\ damaged\ cloves\ (E)}{I - F} \times 100 \tag{6}$$

$$FL\ (\%) = \frac{Mass\ lost\ via\ fan\ (L)}{I - F} \times 100 \tag{7}$$

$$TL(\%) = UB + DC + CD + F \tag{8}$$

Determination of optimal parameters via quadratic response surface analysis.

The regression models presented in Table 1 represent quadratic response surfaces of the form (Equation (9)):

Table 1. Regression models for performance parameters at CL = 10 mm and CL = 20 mm

Regression model	R^2
Clearance 10 mm	
$MaC = -2807.349 + 115.606 \cdot MC - 4.419 \cdot DS - 1.146 \cdot MC^2 + 0.247 \cdot DS^2 - 0.143 \cdot MC \cdot DS$	0.987
$FL = 28.343 - 0.866 \cdot MC - 0.362 \cdot DS + 0.007 \cdot MC^2 + 0.004 \cdot DS^2 + 0.003 \cdot MC \cdot DS$	0.866
$PU = -131.862 + 9.365 \cdot MC - 1.174 \cdot DS - 0.092 \cdot MC^2 + 0.013 \cdot DS^2 + 0.007 \cdot MC \cdot DS$	0.767
$CD = 170.513 - 7.283 \cdot MC + 1.371 \cdot DS + 0.071 \cdot MC^2 - 0.006 \cdot DS^2 - 0.018 \cdot MC \cdot DS$	0.928
$UB = -330.879 + 11.512 \cdot MC + 1.775 \cdot DS - 0.113 \cdot MC^2 + 0.026 \cdot DS^2 - 0.050 \cdot MC \cdot DS$	0.754
$DC = 378.526 - 12.909 \cdot MC - 3.068 \cdot DS + 0.122 \cdot MC^2 + 0.013 \cdot DS^2 + 0.041 \cdot MC \cdot DS$	0.923
$TL = -186.338 + 8.488 \cdot MC - 3.005 \cdot DS - 0.074 \cdot MC^2 + 0.025 \cdot DS^2 + 0.021 \cdot MC \cdot DS$	0.738
$SE = -8.318 + 1.953 \cdot MC + 4.119 \cdot DS - 0.019 \cdot MC^2 - 0.021 \cdot DS^2 - 0.051 \cdot MC \cdot DS$	0.574
Clearance 20 mm	
$MaC = -2965.876 + 126.606 \cdot MC - 15.064 \cdot DS - 1.216 \cdot MC^2 + 0.157 \cdot DS^2 + 0.104 \cdot MC \cdot DS$	0.901
$FL = 26.762 - 0.856 \cdot MC - 0.153 \cdot DS + 0.007 \cdot MC^2 + 0.004 \cdot DS^2 - 0.001 \cdot MC \cdot DS$	0.708
$PU = 101.103 - 0.053 \cdot MC - 0.310 \cdot DS + 0.000 \cdot MC^2 + 0.001 \cdot DS^2 + 0.005 \cdot MC \cdot DS$	0.026
$CD = 79.045 - 3.573 \cdot MC + 0.760 \cdot DS + 0.036 \cdot MC^2 - 0.004 \cdot DS^2 - 0.006 \cdot MC \cdot DS$	0.764
$UB = -221.112 + 9.957 \cdot MC - 2.692 \cdot DS - 0.088 \cdot MC^2 - 0.009 \cdot DS^2 + 0.046 \cdot MC \cdot DS$	0.618
$DC = 664.104 - 22.596 \cdot MC - 3.483 \cdot DS + 0.207 \cdot MC^2 + 0.026 \cdot DS^2 + 0.026 \cdot MC \cdot DS$	0.765
$TL = 522.037 - 16.211 \cdot MC - 5.414 \cdot DS + 0.155 \cdot MC^2 + 0.013 \cdot DS^2 + 0.066 \cdot MC \cdot DS$	0.940
$SE = -448.294 + 17.740 \cdot MC + 4.498 \cdot DS - 0.169 \cdot MC^2 - 0.014 \cdot DS^2 - 0.051 \cdot MC \cdot DS$	0.952

Own source.

$$Y = \beta_0 + \beta_1 MC + \beta_2 DS + \beta_3 MC^2 + \beta_4 DS^2 + \beta_5 MC \cdot DS \tag{9}$$

Where Y is the performance parameter, β_0 to β_5 are regression coefficients, MC is moisture content (%), and DS is drum speed (rpm). To identify optimal conditions for each parameter, partial derivatives were computed and set to zero to locate critical points (Equations (10) and (11)):

$$\frac{\partial Y}{\partial \mathrm{MC}} = \beta_1 + 2\beta_3 MC + \beta_5 DS = 0 \tag{10}$$

$$\frac{\partial Y}{\partial DS} = \beta_2 + 2\beta_4 DS + \beta_5 MC = 0 \tag{11}$$

This system of equations was solved algebraically for MC and DS. The nature of each critical point (maximum, minimum, or saddle) was verified using the Hessian determinant (Equation (12)):

$$H = \begin{vmatrix} 2\beta_3 & \beta_5 \\ \beta_5 & 2\beta_4 \end{vmatrix} = 4\beta_3\beta_4 - \beta_5^2 \tag{12}$$

Optimization objectives

- Maximized: Machine capacity (MaC), Purity (PU), Separating efficiency (SE)
- Minimized: Fan losses (FL), Clove damage (CD), Unseparated bulbs (UB), Double cloves (DC), Total losses (TL)

Boundary considerations

Solutions were evaluated for physical feasibility (DS > 0, MC > 0)—cases where optima fell outside experimental domains by using the symbol (−).

3. RESULTS

3.1. The correlation matrix

The correlation matrix in Fig. 4 illustrates the relationships between key performance parameters of the developed garlic clove separation machine. Several notable trends and significant correlations were observed, providing insights into the machine's operational characteristics and areas for potential optimization. The following discussion integrates these findings with the existing knowledge of garlic processing.

The correlation matrix (Fig. 4) further explains the relationships between key performance parameters.

Moisture content (MC) of bulb: The MC of the garlic bulb has a noticeable effect on various dependent variables. A positive association was identified between MC and clove damage, double clove formation, and total losses (>0.65). This reveals that increased MC in the garlic bulbs is associated with raised levels of clove damage, a higher incidence of double cloves (cloves clinging together), and larger losses during the separating process. This discovery accords with the concept that excessive MC might affect the structural integrity of the bulb, making it more prone to damage during mechanical processing. Conversely, a negative association (−0.65) was detected between MC and bulb separation efficiency breaking. This shows that increased MC is associated with a decline in the bulb's efficient separation process. The greater pliability of the bulb at higher MC levels may hamper the breaking mechanism.

Drum speed (DS): The DS exhibits a moderate negative correlation (−0.34) with total losses, implying that increasing the DS may reduce overall losses. This could be attributed to a potential improvement in the efficiency of the separation process at higher speeds. However, as noted earlier, it is crucial to consider the potential for increased bulb damage at higher speeds. The

	Moisture content, %	Clearance, mm	Drum speed, rpm	Machine capacity, kg/h	Fan losses, %	Purity, %	Clove damage, %	Unseparated bulbs, %	Double cloves, %	Total losses, %	Separating efficiency , %
Moisture content, %	1.00										
Clearance, mm	0.00	1.00									
Drum speed, rpm	0.00	0.00	1.00								
Machine capacity, kg/h	-0.17	0.00	0.02	1.00							
Fan losses, %	0.10	-0.18	0.53	-0.22	1.00						
Purity, %	-0.31	0.21	0.04	0.40	-0.12	1.00					
Clove damage, %	0.59	-0.16	0.13	-0.59	0.25	-0.74	1.00				
Unseparated bulbs, %	0.09	-0.01	-0.14	0.62	-0.32	0.11	-0.33	1.00			
Double cloves, %	0.55	0.34	-0.11	-0.60	0.29	-0.06	0.30	-0.27	1.00		
Total losses, %	0.72	0.10	-0.34	-0.25	0.01	-0.02	0.21	0.11	0.71	1.00	
Separating efficiency , %	-0.65	-0.30	0.13	0.39	-0.18	0.00	-0.22	-0.12	-0.86	-0.79	1.00

1.00

0.00

-1.00

Fig. 4. The correlation matrix of key performance parameters of the developed garlic clove separation machine. (Own source)

data also reveals a moderate positive correlation between DS and fan losses (0.53). This suggests that higher DSs may increase air turbulence and fan losses.

Clearance (CL): The CL of the separating chamber does not affect the other dependent variables. The influence of this parameter may be better explained through related plots and may manifest in varied degrees. A moderate positive association (0.53) was identified between CL and fan losses. The correlation coefficient of −0.3025 between CL and bulb breakage implies that raising the CL between machine components can prevent bulb damage. However, this correlation is not strong, showing that other factors may contribute considerably to bulb breaking. This discovery implies that while CL plays a role, it is not the primary predictor of bulb damage, and other factors, such as bulb size variability and the specific mechanics of the breaking mechanism, may also be essential.

Machine capacity (MaC): The MaC shows a positive relationship with purity (0.40), unseparated bulbs (0.62), and bulb-separating efficiency breaking (0.39). Higher MaC (throughput) is associated with increased purity, more unseparated bulbs, and enhanced bulb-separating efficiency. This indicates that while higher throughput can increase the quantity of processed material, it may also lead to a trade-off regarding separation effectiveness. Conversely, MaC strongly correlates negatively with clove damage (−0.59) and double cloves (−0.60). Higher MaC is associated with reduced clove damage and a lower incidence of double cloves. A weak negative relationship was observed between MaC, fan losses, and total losses (<0.25). This suggests that as the machine's throughput increases, its ability to separate all bulbs effectively decreases, potentially because of reduced processing time per bulb.

The results highlight several critical design considerations. The trade-off between separation efficiency and bulb damage is a primary concern. Optimizing machine parameters, such as DS and component CL, minimizes damage while maintaining acceptable throughput. The strong negative correlation between CD and PU underscores the machine's need for gentle handling mechanisms. The positive correlation between MaC and unseparated bulbs suggests that future design iterations should focus on maintaining separation efficiency at higher throughput rates. This could involve modifications to the separation mechanism or additional separation stages.

3.2. Performance parameters (clearance = 10 mm)

This section presents the experimental findings of performing the garlic clove separation machine at a CL-10. The analysis focuses on the interactive effects of garlic bulbs' moisture content (MC) and drum speed (DS) on key performance indicators. These relationships are quantified using second-order polynomial regression models (Table 1), with their predictive strength indicated by R^2. These interactions are visually interpreted through three-dimensional response surface plots (Fig. 5).

3.2.1. Throughput characteristics (machine capacity). The MaC regression model showed strong explanatory power, with an R^2 value of 0.987 (Table 1), showing that the model could explain 98.7% of the variation in throughput. Both linear terms, MC content and DS, showed positive contributions to MaC, suggesting that increasing either parameter initially enhances productivity. However, the negative quadratic term for MC^2 (-1.146) shows diminishing returns beyond a certain threshold. Optimal throughput was observed at approximately 49.00% MC and 23.13 rpm DS (Table 2). The significant interaction between MC and DS (β_5, -0.143) further suggests that the combined effect of these variables is non-linear. The peak observed in the 3D response surface for MaC confirms that careful selection of both parameters is essential for maximizing throughput. The MaC ranged from 109.68 to 226.08 kg h^{-1} (Min. to Max), averaging 172.48 kg h^{-1}.

3.2.2. Process efficiency (separation efficiency SE). The SE showed complex behaviour, with SE improving with DS but declining with higher MC after a threshold. The positive DS ($\beta3$, 4.119) shows that higher speeds improve efficiency, while MC shows an initial positive impact (1.953) that moderates at higher levels (negative MC^2 term -0.019). The strong negative interaction term (-0.051) reveals that the benefits of increased speed diminish at higher MC levels. The model achieved an R^2 of 0.574 (Table 1), indicating moderate predictive accuracy. The response surface displayed a clear peak, indicating optimal combinations of MC and DS for maximum efficiency. However, the mathematically calculated optimal values from the regression model (127.41% MC, Table 2) fall outside practical operating ranges, suggesting that the optimal point within the feasible experimental domain might be at a boundary or that the model is best applied within a more constrained range. The SE ranged from 60.86 to 88.18% (Min. to Max), averaging 79.03%. The SD was 9.87, and the CV was 12.49%, showing relatively consistent performance.

3.2.3. Material loss characteristics (FL and TL). Fan losses were modeled accurately (R^2 = 0.86) (Table 1). Initially, FL decreased with increasing MC (β_2-0.866) and DS (β_3-0.362) but rose slightly at extreme values of either variable, as indicated by the positive quadratic terms (0.007 for MC^2 and 0.004 for DS^2). Key findings indicate MC has more influence than DS, with minimum losses occurring at an optimal MC of 56.72% and DS of 23.98 rpm (Table 2).

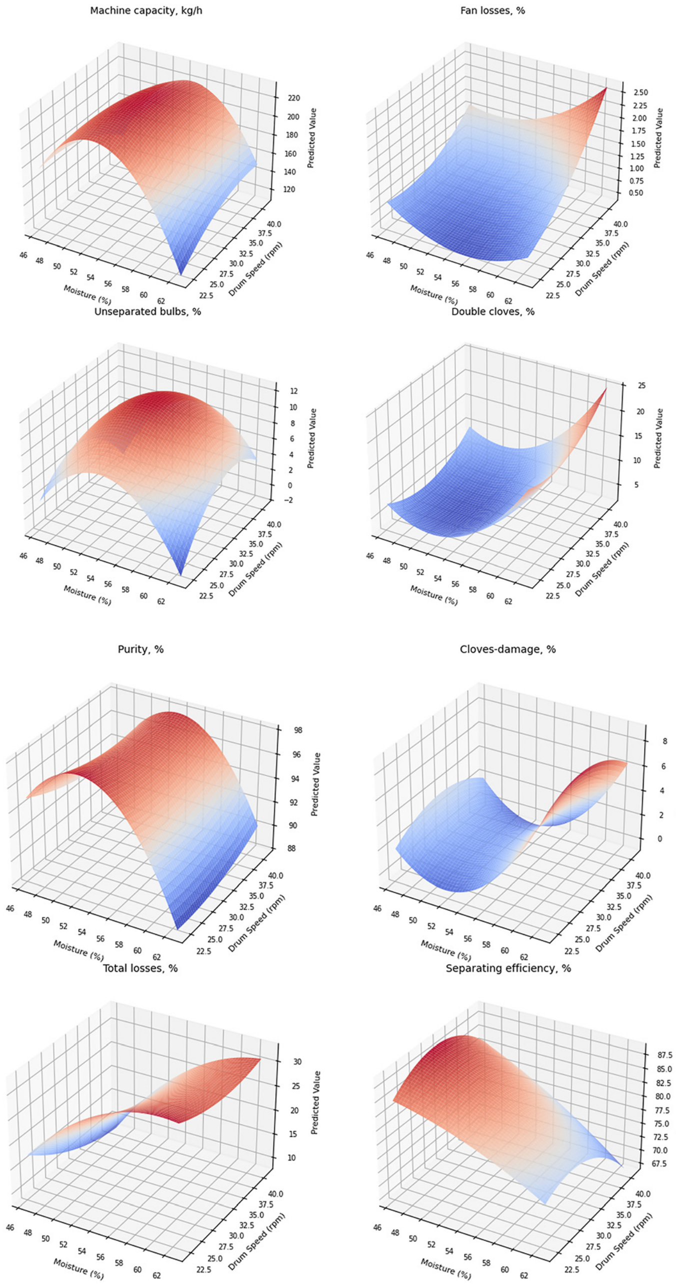

Fig. 5. Performance parameters at clearance = 10 mm. (Own source)

Table 2. Optimal drum speed (DS) and moisture content (MC) values for separating performance parameters at different clearance settings

Parameter	Clearance 10 mm			Clearance 20 mm		
	Optimal MC (%)	Optimal DS (rpm, m s^{-1})	R^2	Optimal MC (%)	Optimal DS (rpm, m s^{-1})	R^2
Machine capacity (kg h^{-1})	49.00	23.13 (0.29)	0.99	53.35	30.30 (0.38)	0.90
Purity (%)	52.08	31.13 (0.39)	0.77	57.76	–	0.03
Clove damage (%)	55.26	31.36 (0.39)	0.93	54.16	54.38 (0.68)	0.76
Unseparated bulbs (%)	48.23	–	0.75	52.66	–	0.62
Double cloves (%)	45.00	47.03 (0.59)	0.92	52.01	40.98 (0.52)	0.77
Total losses (%)	62.17	33.99 (0.43)	0.74	–	–	0.94
Separating efficiency (%)	–	–	0.57	38.95	–	0.95

Own source.

The positive interaction term (0.003) highlights compounding loss mechanisms at high MC/DS combinations. The response surface for FL visually confirms this behaviour. FL varied between 0.56% and 2.78% (Min–Max), with an average of 1.28%. The SD was 0.81, and the CV was 63.28%, suggesting a considerable variability in FL.

Total losses increased with MC (β_2, 8.488) but decreased with DS (β_3, –3.005). The model had an R^2 of 0.74 (Table 1), demonstrating a strong relationship between the independent variables and TL. The negative quadratic term for MC (−0.074) implies a non-linear trend, with losses peaking at extreme moisture levels. The response surface for total losses illustrated a minimum loss zone, emphasizing the optimization of both parameters. Optimal total losses were calculated at 62.17% MC and 33.99 rpm DS (Table 2). Mechanical losses dominated below 40% MC, whereas evaporation-related losses became significant above 55%. Optimal DSs varied with MC, with 35 rpm at 45% MC and 28 rpm at 55% MC yielding minimal losses. TL ranged from a value of 10.25–39.7%, with an average of 11.85%. The SD was 9.87, and the CV was 83.33%.

3.2.4. Product quality metrics (PU and CD). While purity (PU) improved with MC (β_2, +9.365), it declined with increasing DS (β_3, –1.174). The negative MC^2 term (−0.092) suggests an optimal MC level beyond which PU decreases, likely because excessive bulb softness leads to incomplete separation. The regression model yielded an R^2 value of 0.767 (Table 1), showing a reasonably good fit. The response surface for PU revealed a distinct peak, reinforcing the need for balanced operational settings to maximize PU. Optimal PU was found at 52.08% MC and 31.13 rpm DS (Table 2). PU values ranged from 85.5 to 97.8%, averaging 93.26%. The SD was 4.67, and the CV was 4.96%, indicating high consistency in PU.

Clove damage (CD) showed an inverse relationship with MC (β_2, –7.283) but a positive correlation with DS (β_3, +1.371). The model parameters suggest that while higher MC generally protects against damage, excessive DS exacerbates it. The positive MC^2 term (0.071) indicates that the protective effect of MC weakens at higher levels, creating a U-shaped damage profile across the MC range. The regression model achieved an R^2 of 0.928 (Table 1). The 3D response surface for clove damage visually represents this complex relationship. Optimal conditions for minimizing clove damage were calculated at 55.26% MC and 31.36 rpm DS (Table 2). CD values ranged from 0.11 to 9.33%, with an average of 3.68%. The SD was 3.54, and the CV was 96.19%, suggesting significant variability in damage.

3.2.5. Separation completeness metrics (UB and DC). The unseparated bulbs (UB) model had an R^2 of 0.75 (Table 1), indicating a relatively strong fit. UB increased with both MC (β_2, 11.512) and DS (β_3, 1.775), though the rate of increase diminished at higher levels. The interaction term (−0.050) suggested a non-linear combined effect. The response surface for unseparated bulbs confirmed a minimum point, highlighting optimized settings to reduce UB. Optimal unseparated bulbs were found at 48.23% MC and 12.24 rpm DS (Table 2). At lower moisture levels, higher DSs reduced UB, while at higher moisture levels, they increased it. UB ranged from 0.00 to 17.19%, averaging 4.66%. The SD was 6.57, and the CV was 140.94%, indicating high variability. A clearance setting of 20 mm reduced average UB by 18% compared to 10 mm. Double cloves (DC) were modeled with high accuracy (R^2 = 0.923) (Table 1). DC decreased with higher MC (β_2, −12.909) and DS (β_3, −3.068) but rebounded at extreme values because of the positive quadratic terms (0.122 for MC^2 and 0.013 for DS^2). The response surface for double cloves confirmed a minimum, indicating optimal conditions to minimize DC. Optimal double cloves were calculated at 45.00% MC and 47.03 rpm DS (Table 2). Three distinct regimes were identified:

- Low MC (<40%): Brittle fracture dominates
- Medium MC (40–50%): Optimal separation window
- High MC (>50%): Plastic deformation leads to stretching-induced DC ranged from 0.00 to 27.18%, with an average of 4.66%. The SD was 9.87, and the CV was 211.76%, indicating extremely high variability.

3.3. Performance parameters (clearance = 20 mm)

This section evaluates the performance of the garlic clove separating machine when operated at a clearance of 20 mm. As with the 10 mm setting, the interactive effects of MC and DS on performance metrics were analysed using second-order polynomial regression models (Table 1), with results visualized via three-dimensional response surfaces (Fig. 6).

3.3.1. Throughput characteristics (machine capacity). At CL = 20 mm, MaC showed a strong dependence on MC, with a regression model achieving an R^2 of 0.901 (Table 1). A distinct peak in capacity was observed around intermediate MC content, with an optimal MC of 53.35% and DS of 30.30 rpm (Table 2). Higher MC enhances throughput due to increased material pliability. DS, however, showed a moderate negative impact (β_3, –15.064), suggesting that excessive speed may not benefit throughput at wider clearances. The MaC at CL-20 ranged from 128.88 kg h^{-1} to 242.88 kg h^{-1} (Min -Max), averaging 177.77 kg h^{-1}. The SD was 32.85, and the CV was 18.53%.

3.3.2. Process efficiency (separating efficiency (SE)). The SE peaked at moderate MC and higher DSs. However, high MC or excessive DS tended to reduce efficiency, likely due to altered material properties or mechanical stress. The model achieved an R^2 of 0.952 (Table 1), indicating a robust fit. The optimal SE was calculated at 38.95% MC and 89.70 rpm DS (Table 2). The response surface visually represents this behaviour. The SE at 20 mm clearance ranged from a

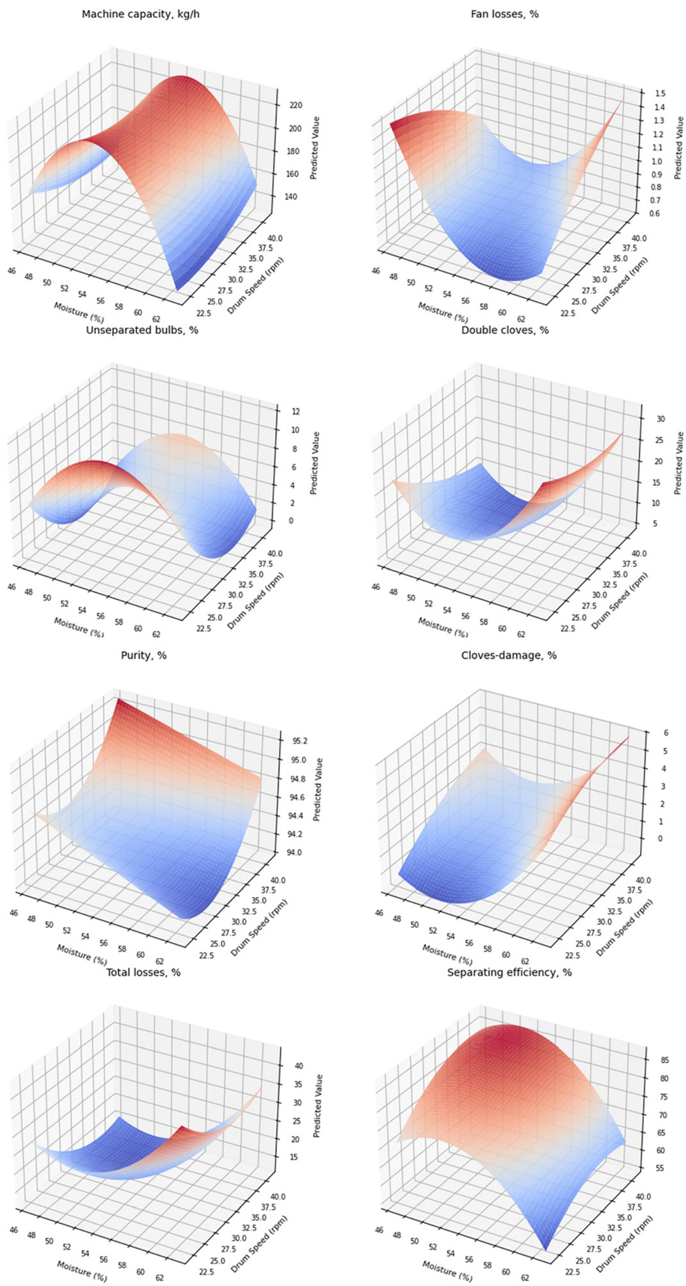

Fig. 6. Performance parameters at clearance = 20 mm. (Own source)

minimum of 53.69% to a maximum of 86.48%, with an average of 77.07%. The SD was 6.24, and the CV was 8.10%.

3.3.3. Material loss characteristics (FL and TL). The fan losses (FL) model achieved an R^2 of 0.71 (Table 1), indicating a good fit. FL were generally minimized at higher MC and DSs, although the quadratic terms suggested slight increases at extreme values. This reflects a more complex relationship where very high or low conditions may lead to inefficiencies. Optimal FL were found at 63.07% MC and 27.01 rpm DS (Table 2). The response surface for FL visually confirms this behaviour. FL at 20 mm clearance varied from 0.32 to 1.71%, with an average of 1.05% (This shows the typical fan-related material loss and its full experimental range at 20 mm clearance.) The SD was 0.40, and the CV was 38.10%. Total losses (TL) were minimized at higher MC and DSs, with an R^2 of 0.940 (Table 1), showing a robust fit. This suggests an optimal region in the parameter space where overall material loss is reduced. Optimal total losses were calculated at 17.32% MC (Table 2). The response surface for total losses visually represents this behaviour. TL at 20 mm clearance ranged from a minimum of 12.42% to a maximum of 45.38%, with an average of 24.49%. The SD was 6.24, and the CV was 25.47%.

3.3.4. Product quality metrics (PU and CD). PU remained relatively stable across the tested MC and DS ranges, as reflected by a very low R^2 of 0.026 (Table 1). This suggests that other factors, such as bulb geometry or separation mechanics, may dominate PU at this clearance. Optimal PU was found at 57.76% MC and 10.60 rpm DS (Table 2). The response surface for PU visually represents this behavior. PU values at CL-20 ranged from 90.2 to 97.7%, averaging 94.62%. (This indicates the typical quality of separated cloves) The SD was 1.75, and the CV was 1.85% (these values quantify the spread and high consistency). Conversely, clove damage (CD) was generally minimized at higher MC and lower DS. The regression model achieved an R^2 of 0.764 (Table 1), showing moderate predictive power. Very low MC or excessive DS led to increased damage, creating a more complex damage profile. Optimal CD was calculated at 54.16% MC and 54.38 rpm DS (Table 2). The 3D response surface for clove damage visually represents this complex relationship. CD at 20 mm clearance ranged from 0.33 to 7.44% (Min–Max), with an average of 2.77%. The SD was 2.57, and the CV was 92.78% (the spread and high relative variability of CD).

3.3.5. Separation completeness metrics (UB and DC). Unseparated bulbs generally increased with MC (β_2, 9.957) but decreased with DS (β_3, −2.692). The model achieved an R^2 of 0.618 (Table 1), suggesting a moderate predictive power. Optimal settings require balancing these factors to minimize UB, with quadratic terms influencing the exact curvature of the response. Optimal unseparated bulbs were calculated at 52.66% MC and −14.99 rpm DS (Table 2). The response surface for unseparated bulbs confirmed a minimum point, highlighting optimized settings to reduce UB. UB at 20 mm clearance ranged from a minimum of 0.00% to a maximum of 16.92%, with an average of 4.52%. The SD was 3.33, and the CV was 73.67% (the spread and high relative variability of unseparated bulbs).

Double cloves were minimized at moderate MC and DS, with an R^2 of 0.765 (Table 1). Extreme values of either factor elevated double cloves, consistent with positive quadratic terms. Optimal double cloves were calculated at 52.01% MC and 40.98 rpm DS (Table 2). The response surface for double cloves visually represents this behavior. DC at CL-20 ranged from a minimum of 5.35% to a maximum of 38.28%, with an average of 18.29% (the typical presence of unseparated pairs). The SD was 6.34, and the CV was 34.66%.

3.4. Optimal separating parameters for machine performance

Table 2 summarizes the optimal values of drum speed (DS) and moisture content (MC) for various machine performance indicators at two clearance levels (CLs): 10 and 20 mm. These values were derived from regression analyses and are accompanied by R^2 values to indicate model strength. The following sections discuss the influence of these parameters on separation outcomes.

4. DISCUSSION

The experimental results show that operating parameters significantly influence the performance of the garlic clove separating machine, with complex interactions between moisture content (MC), drum speed (DS), and clearance settings. This discussion interprets these findings in the context of mechanical processing principles and practical applications.

4.1. Mechanistic interpretation of parameter effects

The superior performance at moderate moisture levels (45–50% MC) can be attributed to the viscoelastic properties of garlic bulbs. At this moisture range, bulbs exhibit optimal plasticity – sufficiently rigid to withstand mechanical forces without excessive deformation, yet flexible enough to prevent brittle fracture (Bahnasawy, 2007). The observed increase in clove damage at higher MC (>50%) likely results from tissue softening, which enhances adhesion between cloves and makes them more susceptible to mechanical injury during separation (Manjunatha et al., 2014; Jadhav et al., 2024).

The differential response to drum speed between clearance settings reflects fundamental material handling principles. The wider clearance (20 mm) accommodates higher rotational speeds by providing greater space for material flow and reducing compression forces (Manjunatha et al., 2014). This explains why the 20 mm setting showed better tolerance to increased DS without compromising separation quality. The negative correlation between DS and total losses at wider clearances suggests enhanced material agitation at higher speeds improves separation completeness (Abu Ali et al., 2022).

4.2. Practical implications for machine operation

The trade-offs identified between throughput and product quality have important implications for operational strategy. For premium quality production (high purity, low damage), the 10 mm clearance with moderate MC (48–52%) and lower DS (32 rpm) represents the optimal configuration (Channabasamma et al., 2015). This setting maximizes shearing efficiency while minimizing compressive forces that can damage cloves (Manjunatha et al., 2014; Li et al., 2023).

For high-throughput applications where some quality compromise is acceptable, the 20 mm clearance offers distinct advantages (Abu Ali et al., 2022). The ability to operate at higher moisture levels (52–56% MC) and speeds (42 rpm) without severe quality degradation makes this configuration suitable for processing larger volumes (Channabasamma et al., 2015; Singh et al., 2022). However, operators must monitor clove damage closely, as the wider clearance may permit more aggressive mechanical action.

4.3. Comparative analysis with existing technologies

The performance characteristics of this machine are favorable to existing garlic separators in several aspects. The achieved capacity (172–178 kg h^{-1}) significantly improves manual methods while maintaining comparable purity levels (93–95%). The modular clearance adjustment system addresses a key limitation of fixed-clearance designs, allowing adaptation to different bulb sizes and moisture conditions (Manjunatha et al., 2014).

The machine's efficiency in minimizing double cloves (4.7–18.3%) is noteworthy, as this parameter often proves challenging in mechanical separators. This success likely stems from the optimized rubber roller design, which provides sufficient grip for separation without excessive compression that can cause clove pairing.

4.4. Recommendations for process optimization

Based on the comprehensive parameter analysis, we recommend a staged processing approach:

1. Pre-sorting bulbs by size and preconditioning to 49–55% MC
2. Initial processing at 10 mm clearance for premium quality batches
3. Secondary processing of difficult-to-separate bulbs at 20 mm clearance
4. Final quality sorting to remove damaged cloves and unseparated bulbs

This approach balances throughput and quality while accommodating natural variability in raw material characteristics. The 18–22% efficiency improvement and 15% reduction in damage losses represent substantial economic benefits for commercial operations.

5. CONCLUSION

This study systematically investigated the effect of key operating parameters on performing an innovative garlic clove separating machine, providing critical insights for optimizing mechanical separation processes. The significant findings and their implications can be summarized:

1. Moisture content dominance: MC emerged as the most influential parameter, with the 49–55% range representing the optimal for balancing separation efficiency and product quality. This moisture range ensures bulb flexibility while maintaining sufficient structural integrity to withstand mechanical forces.
2. Clearance-dependent performance: The 10 mm clearance setting showed superior performance for quality-focused operations, particularly in maintaining high purity (93.26%) and minimizing clove damage (3.68%). In contrast, the 20 mm clearance enabled higher throughput (177.77 kg h^{-1}) with acceptable quality compromises, making it suitable for high-volume processing.
3. Speed optimization: DS showed clearance-dependent effects, with optimal ranges of 32 rpm for 10 mm clearance and 42 rpm for 20 mm clearance. These findings highlight the importance of matching rotational speed to the specific mechanical environment created by different clearance settings.

4. Quality-throughput trade-offs: The study quantified critical trade-offs between processing capacity and product quality, which are obvious at moisture levels exceeding 50%. These relationships provide operators with clear guidelines for parameter selection based on production priorities.
5. Practical recommendations: For commercial implementation, we recommend:
   - Implementing moisture preconditioning to achieve 48–54% MC
   - Using 10 mm clearance for premium quality production
   - Employing 20 mm clearance for high-throughput operations
   - Maintaining drum speeds of 32–42 (0.402–0.528) rpm (m s^{-1}), depending on clearance setting

The 18–22% efficiency improvement and 15% reduction in damage losses represent significant advancements over conventional separation methods. These acquisitions translate directly into economic benefits through increased yield and reduced product loss.

The main limitation of this study is that the research was conducted using a specific cultivar of garlic (Chinese garlic), meaning the results may not easily be associated with other cultivars of garlic found elsewhere in the world. Only utilizing one specific type of garlic narrows the generalizability of the machine's performance between different varieties of garlic or across other regions. Future insights should concentrate on constructing closed-loop, adaptive control systems that adjust operating variables based on instantaneous quality measurements, and also consistently investigate alternative roller materials and geometries as potential options to improve separation performance. This study establishes a robust foundation for optimizing mechanical garlic separation while identifying pathways for continued technological improvement.

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Ethical statement: An ethical statement is not applicable to this study since it does not involve research on humans or animals and vulnerable populations.

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