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Design, Construction and Assessment of a Garlic Trimming Machine

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This research focuses on the design, construction, and assessment of a garlic trimming machine aimed at reducing manual labor and enhancing processing efficiency for small and medium-scale garlic producers. The primary objective was to develop a machine capable of effectively cutting the roots and stems of garlic bulbs while minimizing physical damage and operational costs. Key shearing and frictional characteristics of garlic stems were determined and integrated into the machine's design.

The evaluation was conducted under varying operational conditions, specifically at three different knife speeds (8.5, 12.1, and 20.5 m·s^{-1}) with three different moisture content levels (47.4, 61.5 and 70.3% wet basis). Performance metrics assessed included machine productivity, damage of garlic bulb, energy consumption, and operating cost. Results indicated that operating the trimming machine at 20.5 m·s^{-1} knife speeds with 61.5% moisture content maximized processing productivity while minimizing bulb damage. The machine demonstrated a processing productivity increase of approximately 1.5 times compared to manual methods and achieved a cost reduction of about 29.2%.

Keywords: Garlic, Trimming machine, Design, Post-harvest processing, Small-scale farming.

Introduction

Garlic (*Allium sativum L.*) is one of the most important and widely cultivated crops around the world, playing a significant role in culinary, medicinal, and commercial sectors (Tesfaye, 2021). Its use as a seasoning, condiment, and flavor enhancer makes it an essential ingredient in a variety of cuisines, while its therapeutic properties have been recognized for centuries (Rivlin, 2001).The global demand for garlic has steadily increased over the past decade, driven by its use in food processing industries, pharmaceuticals, and dietary supplements (Bondre *et al*., 2017). This growing demand necessitates the development of efficient post-harvest processing handling techniques to meet market requirements while maintaining product quality and minimizing losses (Sunanta *et al*., 2023).

Post-harvest handling and processing of garlic involve several stages, including harvesting, curing, trimming, and packaging. Trimming, the process of removing roots and stems from garlic bulb is an essential step to prepare the bulbs for market. Traditionally, this process is done manually, particularly in small- to medium-scale farming operations. However, manual trimming is labor-intensive, time-consuming, and prone to inconsistencies in quality, especially when large quantities of garlic are handled (Sunanta *et al*., 2023; Guardia *et al*., 2023). In regions where garlic is produced on a large scale, the manual trimming process becomes a bottleneck in the supply chain, reducing overall efficiency and profitability for farmers (Sun *et al*., 2018). Therefore, mechanization offers a practical solution to these challenges, potentially improving efficiency, reducing labor dependency, and enhancing the overall quality of the harvested garlic.

Mechanization in agriculture has transformed several farming practices by improving productivity, reducing labor costs, and increasing the consistency of agricultural products (Park *et al*., 2021). While crops like grains and vegetables have benefited from extensive mechanization, garlic, due to its relatively delicate structure and irregular bulb shape, presents unique challenges for mechanized processing. Garlic bulbs vary in size, and the roots and stems can have inconsistent thickness and length, making it difficult to standardize trimming processes using traditional machinery (Zhang *et al*., 2023). Moreover, the sensitivity of garlic to physical damage necessitates machines that can handle bulbs delicately to avoid bruising or cutting

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into the bulb, which could lead to faster spoilage and reduced market value.

Currently, few garlic trimming machines are commercially available, and many of them are designed for large-scale industrial use, often out of reach for small to medium-sized farmers due to their high cost and operational complexity (Guardia *et al.*, 2023). These machines, while effective, are often not optimized for handling a variety of garlic sizes or for use in regions with limited access to high-end technological equipment. The need for cost-effective, easy-to-operate, and efficient garlic trimming machines has been increasingly recognized in recent years, especially as the global agricultural sector strives to balance productivity with sustainability (Hu *et al*., 2022).

Previous studies have shown that mechanized garlic trimming can significantly reduce processing time and labor costs while maintaining or even improving the quality of the trimmed garlic bulbs (Zhang *et al.*, 2023). For instance, a study conducted by Guardia *et al*. (2023) found that mechanized trimming reduced processing time by up to 60% compared to manual methods, while also achieving a more uniform cut. Such improvements in processing efficiency can lead to increased profitability for garlic producers, particularly in regions where labor costs are high or where there is a shortage of skilled workers (Zhang *et al*., 2023). In response to these challenges, this research aims to design, construct, and assess a garlic trimming machine that is suitable for small and medium-scale garlic producers. The primary objectives are to develop a machine that can efficiently and uniformly trim garlic bulbs of different sizes, reduce the time and labor required for manual trimming, and minimizes physical damage to the garlic during processing. The machine will be designed with a focus on affordability, ease of operation, and adaptability to varying garlic bulb dimensions and trimming specifications.

This study builds upon previous research in the field of agricultural machinery and post-harvest technology. While several attempts have been made to automate various post-harvest processes in garlic production, there remains a gap in the availability of affordable and effective garlic trimming machines for small-scale farmers. For example, Park *et al*. (2021) explored the mechanization trends in garlic production, noting the advancements in harvesting and curing processes but highlighting the limited progress in developing trimming equipment. Similarly, Guardia *et al*. (2023) conducted a comparative study of manual versus mechanized garlic trimming, demonstrating the clear advantages of mechanized systems in terms of speed and consistency but acknowledging the prohibitive costs for smaller farms.

The objective of this study is to design a cost-effective garlic trimming machine tailored for small and medium-scale farmers, focusing on precise cutting that preserves bulb integrity, accommodates various sizes, and utilizes locally available materials and technologies for ease of maintenance.

Materials and Methods

1. Sample preparation

Following common local practices, the bulbs were dried by spreading them inside a dark room with open windows for a period of 15 days. The moisture content of the garlic was calculated on a wet basis (w.b.) (ASAE, 1999a).

2. Characteristics engineering of garlic bulb and stem

Some characteristics engineering of garlic stem and bulb related to trimming process were determined and taken into account during the trimming machine design.

2.1 Physical characteristics

Some physical characteristics of garlic bulb (Egyptian Baladi variety) were determined according to Ibrahim (2013). Table (1) shows length, width, thickness, mass, volume and bulk density of garlic bulbs.

2.2 Dynamic coefficient of friction characteristics

The dynamic friction coefficient (μd) of garlic bulb, stem, and root on different material types sliding over steel, rubber, and wood surfaces was measured at a moisture content of 70.3% (the moisture content after harvesting) using a specialized apparatus (as shown in Fig. 1). The setup consists of a vertically oriented hollow cylindrical container with an inner diameter of 3.2 cm, mounted at the centre of a horizontal plate carriage (26×13.5×4.5 cm) that moves on four roller wheels (Abd El Rahman *et al*., 2024).

Table 1. The characteristics of garlic bulb.

Characteristic		Average
Length, mm		36.5±3.1
Width, mm		51.4±6.8
Thickness, mm		50.7±5.9
Mass, g		62.5±11.6
Volume, cm^3		36.5±3.1
Bulk density, $g \cdot cm^{-3}$		0.45±0.25
Dynamic friction coefficient	Metal	0.42±0.09
	Wood	0.30±0.08
	Rubber	0.50±0.10

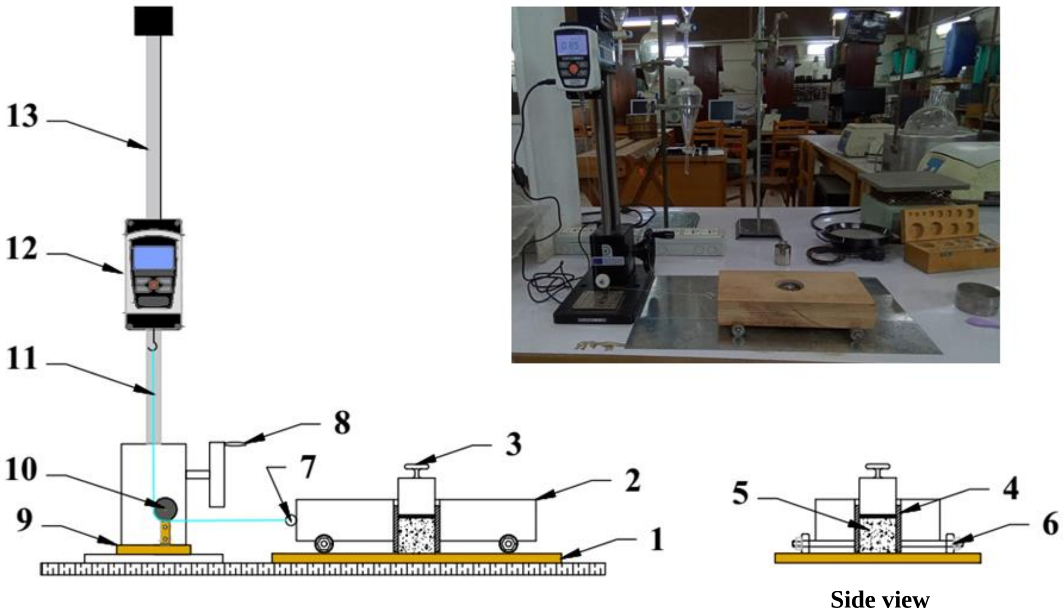


Fig. 1. Setup for measuring the dynamic friction force: 1-Sliding surface, 2-Plate carriage, 3-Calibration masses, 4-Hollow cylindrical, 5- Powder material, 6- Roller wheels, 7- Hook. 8-Hand wheel, 9- Test stand, 10- Small pulley. 11- Wire, 12- Force gauge, and 13- Sliding ruler.

The container's lower end maintains a 1 mm clearance from the tested material surface, which is a 30 cm wide and 50 cm long sheet. Key components of the apparatus include calibration masses, roller wheels for smooth movement, a force gauge (MARK-10, Model M3-10, USA), and other elements to ensure accurate measurement. The combined weight of the sample, masses, and carriage was pulled horizontally to measure the force required to overcome dynamic friction. The dynamic friction coefficient was then calculated using the method described by Marey et al. (2017).

$$\mu_d = \frac{F_f}{N_l} = \frac{F_T - F_E}{N_l} \quad (1)$$

Where μd is the dynamic coefficient of friction, F_f is the friction force ($F_f = F_T - F_E$) (N), FT is force needed to get a filled cylindrical container moving, N; F_E is force needed to get an empty cylindrical container moving, N; and N_l is the normal load pressing the sample to the contact surface, N.
The table (1) shows the values of the dynamic coefficient of friction for different materials.

2.3 Shearing characteristics

The shearing characteristics were conducted in accordance with ASAE (1999 b). A shear box was used to test shear force in a double shear setup (Fig. 2), which consists of three hardened steel plates, two are fixed and the third is sliding freely between fixed plates in a close-fitting arrangement. The specimens were subjected to the shear force, the shear box is connected vertically to a steel rod linked to a digital force gauge (MARK-10, Model M3-10, USA), to measure the force required to induce shearing. The following equation was used to compute the shear stress (τ, MPa):

$$\tau = \frac{F}{2A} \quad (2)$$

Where F is shearing force to cut the sample, N; A is sectional area of the garlic stem, mm^2.

By integrating the area under the shear force and displacement curve, the shearing energy was computed (Chen *et al*., 2004). The specific shearing energy was discovered to be:

$$E_{SC} = \frac{E_S}{A} \quad (3)$$

Where Esc is specific shearing energy of the garlic stem, $mJ \cdot mm^{-2}$; Es is shearing energy of the garlic stem, mJ.

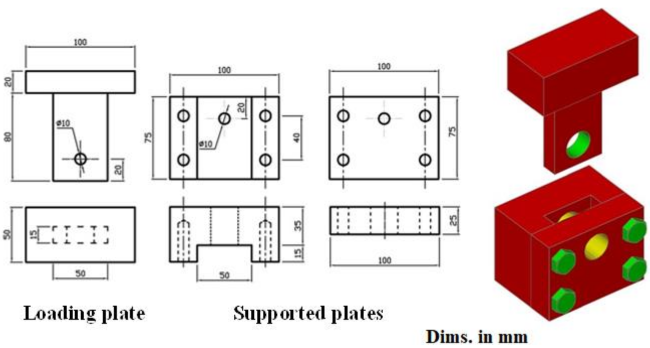


Fig. 2. The double shear setup.

Table 2. Shearing characteristics of garlic stem and root.

Characteristic	Minimum	Maximum	Average	Standard Deviation
		Garlic stem		
Shearing force, N	2.00	7.50	3.94	1.15
Shearing stress, MPa	0.13	0.32	0.22	0.07
Shearing energy, $mJ \cdot mm^{-2}$	0.49	1.36	0.72	0.22
		Garlic root		
Shearing force, N	1.10	3.75	1.98	0.63
Shearing stress, MPa	0.02	0.05	0.03	0.01
Shearing energy, $mJ \cdot mm^{-2}$	0.12	0.34	0.18	0.05

3. Theoretical approach

The circular knives mechanism was used. The circular knives consist of two counter-rotating knives (circular knives) to trimming the garlic stem (Fig. 3). The objective is to trim the garlic stem without damage in the garlic bulbs.

Fig. 3 illustrates a diagrammatic representation of the forces operating on a garlic stem as it travels between two counter-rotating knives. The vertical direction in which the forces balance is indicated by the following equation:

$$2F \sin\theta + W = 2 F_N \cos\theta \quad (4)$$

$$F = \mu F_N \quad (5)$$

Where F is the friction force between the garlic stem and the knife surface; μ is the coefficient of dynamic friction between the garlic stem and the knife; F_N is the normal force; and θ (deg) is the angle between the tangent of contact between the garlic stem (S) and knife (A) or (B) and horizontal plan.

$$2F\left(\sin\theta - \frac{\cos\theta}{\mu}\right) + W = 0 \quad (6)$$

In Fig. 3, the r is the radius of the circular knife (A or B); r_B is the garlic stem radius (S); and W is the garlic bulb and stem weight.

$$2F\left(\frac{\cos\theta}{\mu} - \sin\theta\right) = W > 0 \quad (7)$$

Thus,

$$\cot\theta > 0 \quad (8)$$

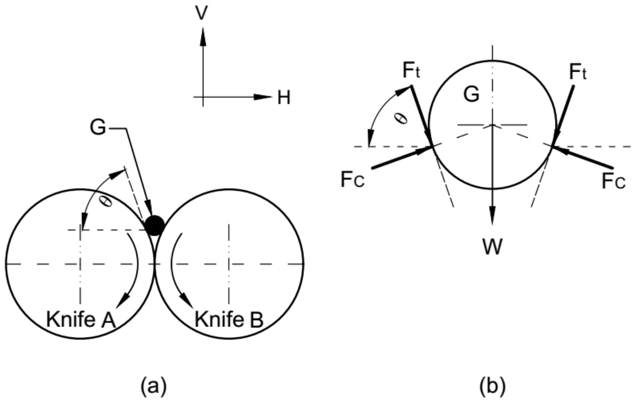


Fig. 3. The exerted forces during trimming process of garlic stem: (a) two circular knives; (b) garlic stem.

On the other hand, according to the Fig. 3, cot θ is expressed as follows:

$$\cot\theta = \frac{\sqrt{(r+r_B)^2-(r)^2}}{r} = \sqrt{\frac{(r+r_B)^2}{(r)^2}-1} \quad (9)$$

Therefore,

$$\sqrt{\frac{(r+r_B)^2}{(r)^2}-1} > \mu \quad (10)$$

Equation (10) determines the upper bound of the knife radius, r, assuming that the garlic stem's radius, r_B, is a constant value and that the coefficient of friction μ is always positive (based on the knives' surface). The horizontal force delivered to the garlic stem (F_H) by the circular knives is the result of the two opposing horizontal forces summation, which are stated as the following equation:

$$F_H = 2(F\cos\theta + F_N \sin\theta) \quad (11)$$

Combining equations (11), (5), and (4) leads to:

$$F_H = W\frac{\mu\cot\theta+1}{\cot\theta-\mu} \quad (12)$$

Where F_H is the greatest horizontal force acting on the garlic stem in Eq. (12). Garlic stems will be trimming if they are exposed to a horizontal force that is greater than this value. As a result, the cutting force, $F_{H,max}$ has the following definition:

$$F_{H,max} > W\frac{\mu\cot\theta+1}{\cot\theta-\mu} \quad (13)$$

Another upper bound on the knives' radius is established by Equation (13). But in this case, $F_{H,max}$ and W are connected to the limit.

It is clear from equation (10) that the material's surface qualities between the knives and the garlic stem need to be chosen. It can be demonstrated that the frictional coefficients (μ) between the surfaces of the knives and the garlic stem are significant variables if the μ is to be used to cut a garlic stem. The μ is shown in Table (1).

A normal compression force (F_N) was calculated by shearing force of garlic stem, it ranges from 2 to 7.5 N (Table 2). Therefore, and the normal compression force (F_N) should be more than shearing force of garlic stem.

The garlic stem's diameter fell between 5.1 to 13.88 mm, as indicated by Table 1. The maximum of 15 mm was determined to be equal the garlic stem radius of the nut, or r_B (knives of the other variety can be used with this). Equation (10) requires that the minimum values of r_B and μ be chosen (r_B = 15 mm and μ = 0.70) and replaced in order to get the maximum radius of the roller, r. Thus, knives with radii more than 70 mm will meet equation (10).

4. Developed machine

The machine's ability to cut the garlic bulb's root and stem at a pace faster than the human approach, its convenience of use, and its economy in making the machine within the means of local farmers were all taken into consideration during the design process. The essential components of the proposed machine are as follows: trimming unit; main shaft; power transmission; and main frame (Fig. 4).
Manual feeding of the garlic plant root-end down is putting into a protected slot, where a guard halts the bulb. Bulbs with stems are inserted horizontally, guided through a mechanism, and cut by a blade. The system adjusts for varying sizes and shapes, trimming stems to a set length. A discharge device beneath the blade collects and releases the trimmed roots through a duct.

4.1 Frame and support

The frame of the constructed machine was built using a hot rolled section steel construction (with yield strength of 235MPa) with an L-angle cross-section measuring 40× 40× 4 mm. This choice of material provides excellent structural stability and strength while maintaining a relatively lightweight design. The dimensions of the frame are 60 cm in length, 50 cm in width, and 70 cm in height, ensuring adequate support for the machine's components. The L-angle steel sections are particularly suitable for resisting bending and torsional forces, making them ideal for handling the operational loads and vibrations generated during the machine's operation. This robust frame design contributes to the overall durability and longevity of the machine.

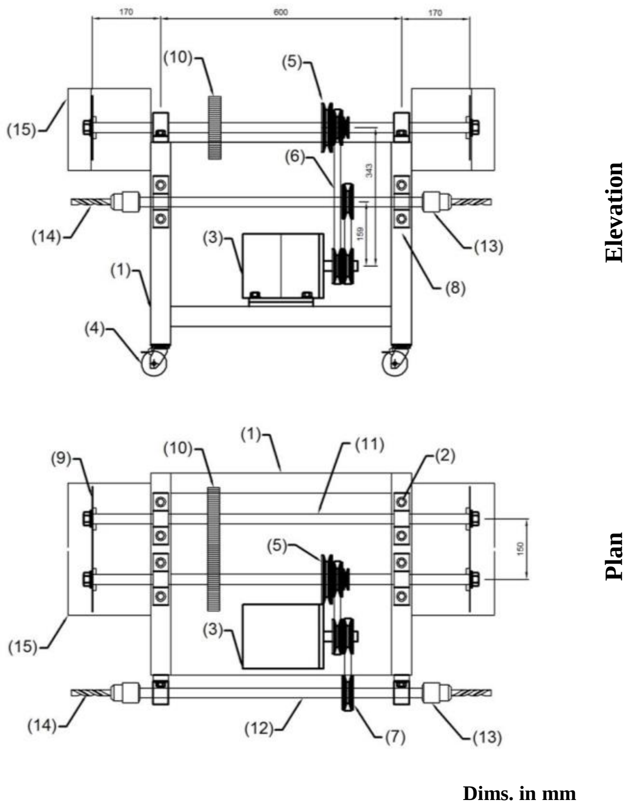


Fig. 4. Constructed trimming machine: 1- Machine base. 2- Bolts and nut. 3- Motor. 4- Bearing. 5- Malti-Pulley. 6- V belt. 7- Single-Pulley. 8- Bearing housing. 9- Circular knife (160 mm diameter). 10- Spur gear (160 mm diameter). 11- Main shaft. 12- Side shaft. 13- Drill chuck. 14- Twist drill (Left and right). 15- Cover.

4.2 Power transmission unit

Three speeds will be the machine's operating: 1020 (8.5), 1440 (12.1), and 2448 (20.5) rpm ($m \cdot s^{-1}$).

4.3 Trimming and cleaning units of garlic stem and root

The trimming machine operates using the shear cutting principle. Two pairs of knife blades mounted on shafts (1, 2) make up the cutting unit. As seen in Fig. 5, the cleaning unit is made up of two twist drills and a drill chuck that are mounted on shaft (3).

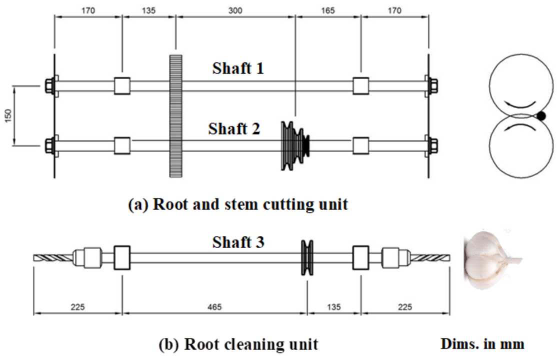


Fig. 5. Trimming and clean units of garlic stem and root.

The power requirement for trimming the garlic stem

The pair of knives in Fig. 3 are represented by A and B, the garlic stem by G, its weight by W, the normal force acting on G by Fc, and the tangential force acting on G by Ft.

The first thing to take into account in the design process is the amount of power requirement to run the machine. Shigley (2015) estimated the amount of power (P, in W) needed to cut the garlic stem as follows:

Power (W) = n_k T ω (14)

Where n_k is Trimming knives number, ($n_k = 4$); ω is trimming knives angular velocity, rad·s^{-1}, ($\omega = 2\pi N_r/60$); N_r is trimming knives revolution velocity, rpm (N_S = 2448 rpm); T is trimming torque, N·m ($T = r F_t$); r is trimming knives radius, m (r = 0.80 m); and F_t is Tangential force, N.

For a single garlic stem, the normal force required to cut it (2 × F_N) was calculated at 7.5 N, as shown in Table 2. The tangential force (F_t) was calculated using a friction coefficient (μ = 0.7), resulting in Ft = μ × FN = 2.625 N. Therefore, two garlic stems can be cut simultaneously. The torque (T) calculated using Equation (16) is 0.21 N·m, and the power requirement to operate the cutting shafts at 2448 rpm is 215.23 W. The selected electric motor power is 0.5 horsepower (P= 375 watts).

The main shaft's (1and 2) design: The different parts (such pulleys) are put on the shaft to transfer the power from it. Shaft design is based on torsional moment, bending, and combined shock and fatigue (Fig. 5).Thus, the shaft's diameter (d, mm) was computed using the formula below (Shigley, 2015):

$$d^3 = \frac{16}{\pi S_s}\sqrt{[K_b M_b]^2 + [K_t M_t]^2} \quad (15)$$

Where M_b is resultant bending moment, N·m; M_t is torsional moment, N-m; K_b is Combined shock and fatigue factor applied to bending moment, (K_b = 1.5); K_t is combined shock and fatigue factor applied to torsional moment (Kt =1.0) and ;Ss is allowable shear stress of the shaft material, MN·m^{-2} (Ss =40 MN·m^{-2}).

By examining moments resulting from both horizontal and vertical loads in the shaft's bending moment diagrams, Mb was computed. The following formula was used to calculate Mt (3.51 N·m):

$$M_t = \frac{P \times 60}{2\pi N} \quad (16)$$

Bending moment in relation to the main shaft: The electric motor's operation causes two tension forces act vertically downward on the main shaft. These forces are typically due to the pulley and belt system connected to the motor. As the motor drives the pulley, the belt exerts these vertical forces on the shaft, creating a bending moment.

For the pulley: weight of pulley (Wp) = **16.3** N. According to ASTM Standards, the V-belt is 16 mm that can transmit 2 – 15 kW.

Belt Force: The belt tensions and speed determine how much power a belt drive can deliver. Khurmi and Gupta (2005) estimated the belt tensioning forces on the pulley as follows: torque transmitted by the pulley (Mt) = 3.51 N·m. The results of the calculations for the force belt tension in the tight side (T_1) and the force belt tension in the loose side (T_2). Hence, Total force (T_1+T_2+Wp) acting on pulley is **297.15 N**.

For the knife: knife weight (W_C) is 3.1 N. Therefore, the normal force exerted by the garlic stem on a single knife is 3.75 N, acting at a 20° angle to the horizontal, as illustrated in Fig. 3. As the load F_N is divided into vertical and horizontal components, the vertical component is equal to 1.28 N and the horizontal component is equal to 3.52 N. F_{TV} (vertical loading) on the shaft is equal to 4.38 N (F_N Sin 20 + W_C) and the horizontal loading (F_{TH}) on the shaft is equal to **3.52 N**.

For the gear: The gear used in the machine has a weight (W_G) of 43.29 N. This weight is a significant factor in the gear's operational dynamics, as it contributes to the overall load on the supporting structure and influences the machine's stability. The acting forces on the gears, which include torque, friction, and any additional external forces, are depicted in Fig. 6. These forces are crucial in understanding the gear's behavior under operational conditions, as they affect the gear's performance, efficiency, and wear. Proper analysis and consideration of these forces ensure that the gear operates smoothly and effectively within the machine.

$$F_t = \frac{P}{r \times \omega} \quad (17)$$

Where Ft is tangential force, N (Fr = Ft × tan ϕ); P is power requirement to trim the garlic stem, W; r is pitch circle radius (r = 77.5 mm); ω is gear angular velocity, in rad·s^{-1}, (ω =2π Ns/60); N_S is gear speed, (1020 rpm); Fr is radial force, N; ϕ is tooth pressure angle (ϕ = 20 °).

Therefore, F_t equals 0.76 N and F_r equals 0.28 N. The horizontal force acting on the gear equals **0.28** N.

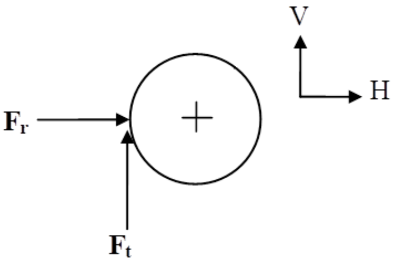


Fig. 6. Acting forces of the gear.

As a result, the vertical loads are shown in Fig. 7 that applied to the shaft. Fig. 7 displays the bending moment diagrams with the different loads.

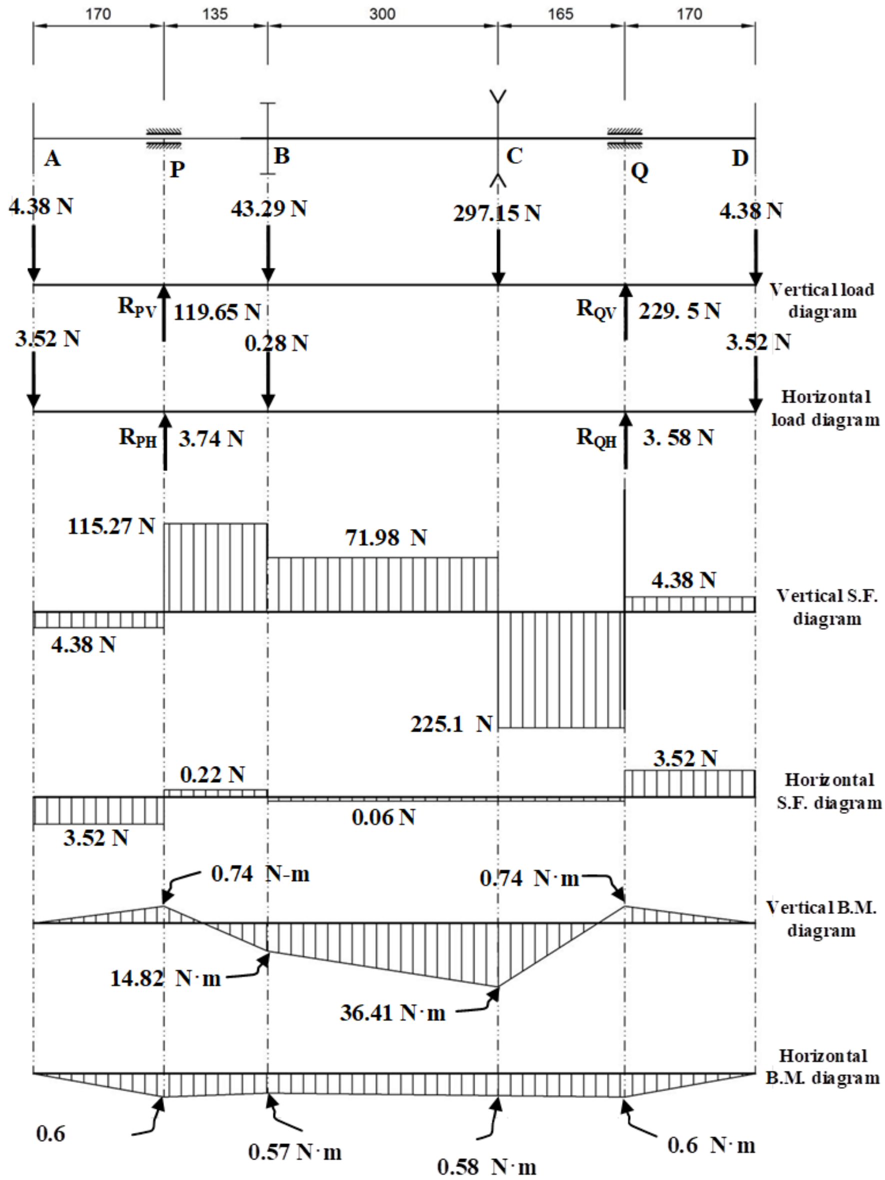


Fig. 7. Shearing forces and bending moment graphs for the main shaft.

It is clear from Fig. 7 shear force diagram at C point is the maximal bending moment (36.41 N·m). Mt = 3.51 N·m was found to be the maximum torque. Shaft diameter (d), as determined by applying equation (17), must equal or exceed 19.13 mm.

4.4 Machine bearing

The machine ball bearing was chosen by consulting the FAG rolling bearing manufacturer's catalog.

4.5 Electric motor

A single-phase electric motor with a power rating of 0.5 horsepower was employed to drive the machine. This motor operates at a rated speed of 1440 revolutions per minute (rpm), providing sufficient torque and power to ensure efficient operation. The motor's speed and power rating were selected to match the requirements of the machine, ensuring that it could handle the necessary load while maintaining consistent performance. The use of a single-phase motor makes it suitable for standard household or small-scale industrial electrical supply, enhancing the machine's adaptability and ease of use in various settings.

5. Main shaft specifications using Finite Element Analysis with ANSYS

The Finite Element Analysis (FEA) and explicit dynamics analysis were employed using ANSYS (version 18.1) to determine the material specifications for the main shaft. Two types of metal specifications were examined (Table 3). The ANSYS program facilitated an investigation into total deformation and equivalent stress (von Mises), both of which impact the performance of the main shaft.

Using the designed dimensions of the main shaft and analyzing the instantaneous effects of forces acting on it (Fig. 8), a comparison was made between two alloys: stainless steel and structural steel. The results indicated minimal differences in total deformation and equivalent stress (von Mises) between the two alloys (Fig. 9). Consequently, structural steel is more cost-effective and efficient compared to stainless steel, which tends to be pricier due to the significant presence of expensive alloying elements.

Table 3: Specifications of Knife and Shaft Materials for ANSYS Analysis.

Material	Density ($g \cdot cm^{-3}$)	Young's Modulus (GPa)	Poisson's Modulus	Yield Strength (MPa)
Stainless Steel	7.90	200	0.31	300
Structural Steel	7.85	200	0.27	300

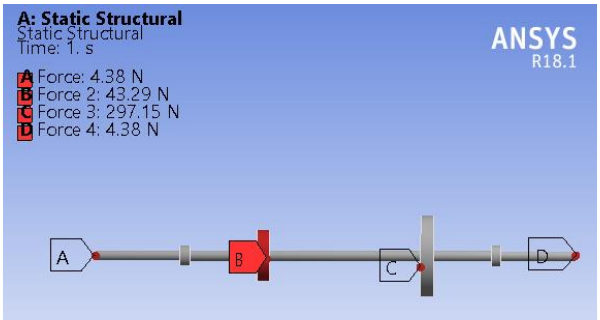


Fig. 8. The vertical loads acting on the main shaft.

6. Assessment criteria

Machine productivity, bulb damage, energy consumption, and cost were the assessment criteria of the constructed machine, (Ibrahim and Athai, 2018; Singh *et al.*, 2022). The trimming machine was assessed at different moisture content levels of garlic and knife speed (Table 4).

Table 4. Experimental treatment for the assessment.

Variables	Value
Moisture content (%)	47.4, 61.5, 70.3
Knife speed ($m \cdot s^{-1}$)	8.5, 12.1, 20.5

6.1 Machine productivity (P_m)

The following formula was used to get the machine productivity (P_m):

$$P_m = \frac{\text{Number of trimming garlic}}{\text{Trimming time}} \quad (18)$$

6.2 Bulb damage (BD)

The following formula was used to get the bulb damage percentage (BD):

$$BD\,(\%) = \frac{\text{Number of bulb damage in the sample}}{\text{Total weight of sample}} \times 100 \quad (19)$$

6.3 Power requirement (PR) and energy consumption (EC)

The following formula was used to determine the necessary electric power requirement (PR) under machine operating load (Chancellor, 1981):

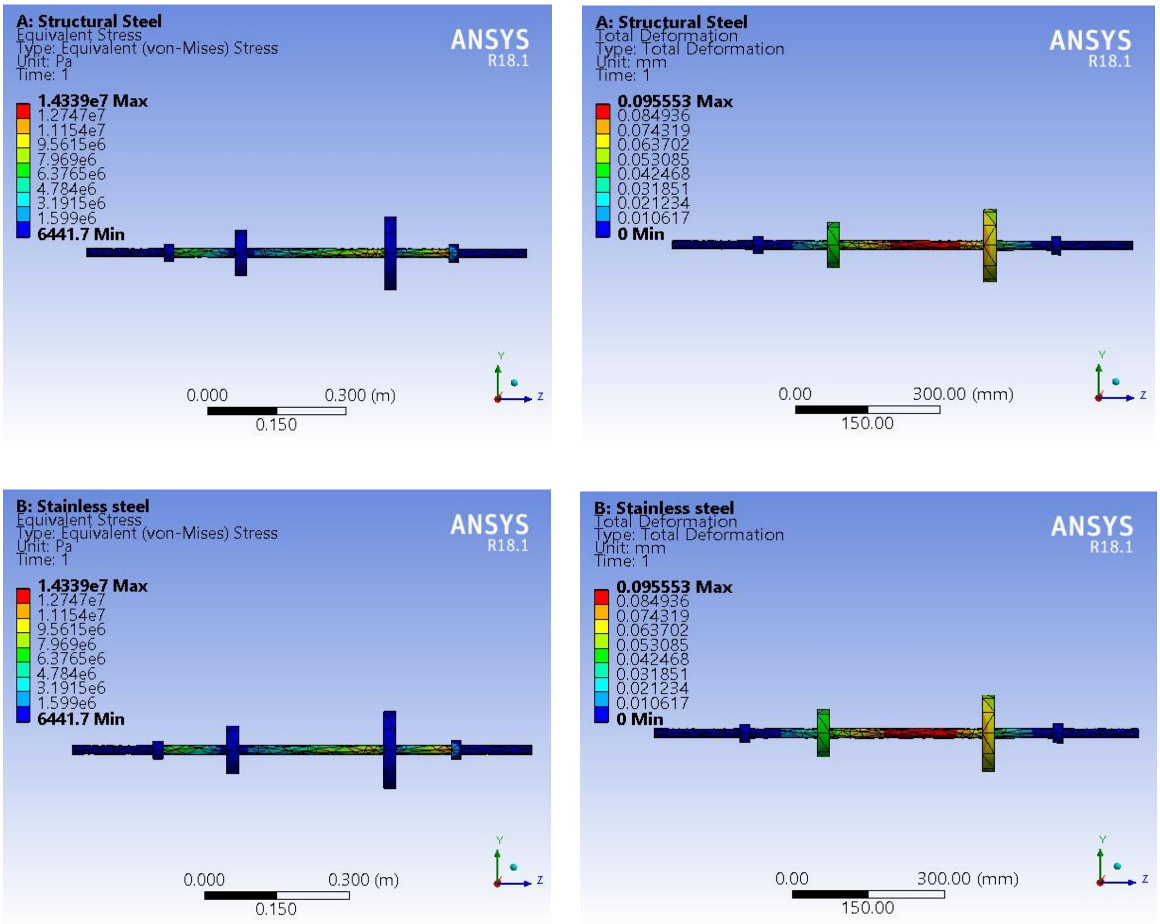
Power requirement (RP) = Volt × Ampere × Power factor (cos θ) (20)

The voltage and current intensity were measured using a Voltmeter and a digital clamp meter, respectively. The specific power per unit productivity, or energy consumption (EC), was computed using the following formula:

Energy consumption (EC) = (PR/Pm) (21)

6.4 Machine operating costs

Machine operating costs (USD•h-1) were determined using the fixed and variable costs (Srivastava et al., 2006). The machine operating costs (USD•piece-1) were determined as the follow: (22)



(a) von Mises Stress **(b) Deformation**

Fig. 9. The von Mises Stress and total Deformations of the main shaft using ANSYS: (A) Structural steel material and (B) Stainless steel alloy for manufacturing the main shaft.

Results and Discussion

1. Machine productivity (P_m)

The machine productivity was affected by both knife speed and moisture content (Fig. 10). As knife speed increased from 8.5 to 20.5 m·s^{-1}, the productivity increased from 522 to 743 pieces per hour. This increase aligns with findings from previous research, which indicates that higher cutting speeds generally enhance processing efficiency in agricultural machinery (Park *et al.*, 2021). However, the decrease in productivity at higher moisture content levels (from 47.4% to 70.3%) suggests that the increased toughness of the garlic stems at higher moisture levels poses a challenge for cutting efficiency (Guardia *et al.*, 2023). This highlights the need for farmers to consider moisture levels during processing to optimize machine performance.

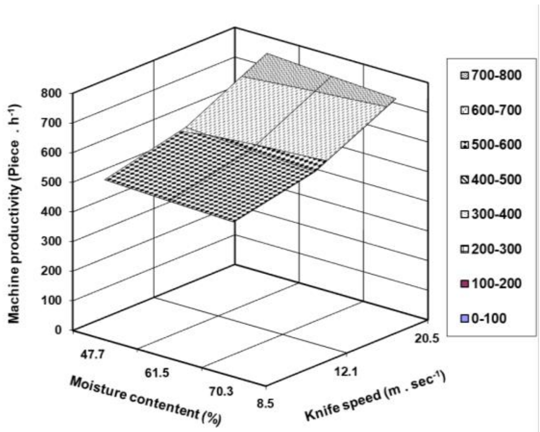


Fig. 10. The machine productivity as a function of different moisture contents and knife speeds.

2. Bulb damage (BD)

The relationship between knife speed and bulb damage is particularly noteworthy. The study found that as knife speed increased, the percentage of bulb damage also increased (Fig. 11). This finding is consistent with the work of Ibrahim (2013), who noted that higher speeds can lead to increased physical stress on the product, resulting in greater damage. Conversely, the study found that higher moisture content resulted in lower bulb damage, indicating that softer garlic is less prone to damage during cutting. This suggests that moisture content plays a crucial role in maintaining product integrity during mechanical processing (Sunanta *et al.*, 2023).

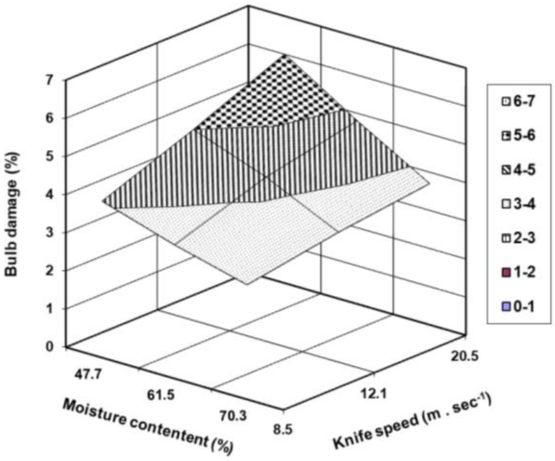


Fig. 11. The bulb damage percentage as a function of different moisture contents and knife speeds.

3. Energy consumption (EC)

With a moisture content of 61.5 to 70.3% and a knife speed of 8.5 to 20.5 $m \cdot s^{-1}$, the energy consumption varied between 0.26 and 0.48 $W \cdot h \cdot piece^{-1}$. The moisture content and knife speed have an impact on the amount of energy used. At the 8.5 $m \cdot s^{-1}$ knife speed, the energy consumption was the least, and it rose as the speed increased because more power was needed to maintain the same speed. As seen in Fig. 12, the energy consumption was about the same at moisture values ranging from 61.5% to 70.3%.The optimal cutting conditions for the machine were found when the moisture content value was 61.5% and the knife speed was between 8.5 and 20.5 $m \cdot s^{-1}$.

The energy consumption of the machine was directly related to both knife speed and moisture content as shown in Fig. 12. Higher knife speeds and lower moisture contents resulted in increased energy consumption. This relationship is supported by the findings of Chen *et al*. (2004), who reported that energy requirements for cutting operations increase with speed. Therefore, optimizing the operational parameters is essential to balance efficiency and energy use, which is critical for the economic sustainability of small-scale farmers.

4. Technical and cost-effectiveness

The economic analysis demonstrated that the cost of trimming garlic stem using the developed machine was approximately USD 0.37 for 100 pieces, compared to USD 0.52 for the manual method, representing a cost reduction of about 29.2%. This finding corroborates the conclusions of previous studies that have highlighted the economic advantages of mechanization in agricultural processes (Sun et al., 2018).

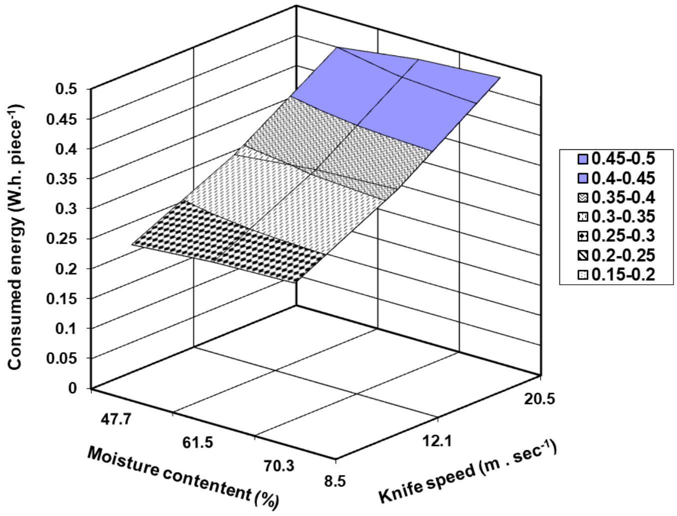


Fig. 12. The energy consumption as a function of different moisture contents and knife speeds.

The enhanced throughput of nearly 1.5 times compared to manual methods further supports the machine's viability as a cost-effective solution for garlic processing (Fig. 13).

In summary, the developed garlic trimming machine shows significant potential for improving processing efficiency and reducing costs for small-scale farmers. However, careful consideration of operational parameters, such as knife speed and moisture content, is essential to minimize bulb damage and optimize energy consumption. These findings contribute to the ongoing discourse on the mechanization of agricultural processes and the need for affordable, effective solutions for smallholder farmers.

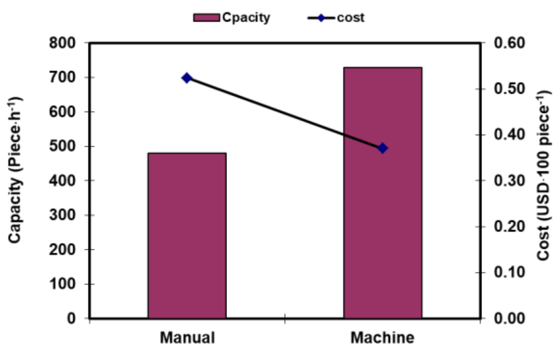


Fig. 11. Productivity and cost of garlic stem trimming with manual method and machine.

Conclusion

The research successfully developed and evaluated a garlic trimming machine designed to enhance the efficiency and economic viability of garlic processing for small and medium-scale farmers. The findings indicate that the machine significantly increases processing productivity, achieving an approximate 1.5-fold improvement over manual methods. This enhancement is primarily attributed to the optimized knife speeds, which, while increasing throughput, also necessitate careful management to minimize bulb damage.

The study highlights the critical balance between operational parameters, such as knife speed and moisture content, in achieving optimal performance. Moreover, the economic analysis reveals a substantial cost reduction of approximately 29.2% in trimming expenses when using the machine compared to manual methods. This reduction not only enhances the profitability of garlic production but also underscores the potential for mechanization to improve the livelihoods of smallholder farmers.

In conclusion, the developed garlic trimming machine represents a significant advancement in agricultural technology, addressing the pressing need for efficient post-harvest processing solutions. Future research should focus on further refining the machine's design and exploring its adaptability to different garlic varieties and processing conditions. By continuing to innovate in agricultural machinery, we can support sustainable farming practices and contribute to the overall growth of the agricultural sector.

Consent for publication
All authors declare their consent for publication.

Author contribution
The manuscript was edited and revised by all authors.

Conflicts of Interest
The author declares no conflict of interest.

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