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CHARACTERIZATION OF THE MECHANICAL PROPERTIES OF GARLIC (*ALLIUM SATIVUM* L.) FOR PROFICIENT EQUIPMENT DESIGN IN FOOD PROCESSING

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ABSTRACT

The present study investigates the mechanical properties of garlic bulbs (GB) and garlic cloves (GC) to facilitate the development of efficient and effective mechanization in food processing. Accurate characterisation of these properties is crucial for designing machinery that can handle garlic without damage, optimize processing parameters and maintain product quality. The research focuses on determining key mechanical attributes of garlic bulbs and cloves, which include coefficient of friction, angle of repose, rupture force and cutting force. A texture analyser was used to measure compression force and cutting force. The compression force for garlic was obtained as, 93.49 N and 52 N in vertical and horizontal orientations, respectively. The angle of repose values for the garlic bulb and garlic clove were calculated as 46.70 ± 1.97° and 40.70 ± 2.04°, respectively. However, the coefficient of friction for garlic bulb and garlic clove was found to be 0.33 ± 0.03 and 0.35 ± 0.03, respectively for stainless steel surface, which is suitable from a hygienic and processing point of view. The obtained data provides valuable insights for engineers designing garlic processing equipment, enabling them to optimise machine design for tasks such as peeling, slicing, dicing and sorting, ultimately leading to improved efficiency, reduced waste and enhanced product quality in mechanised garlic processing.
***Keywords*:** Frictional properties, Garlic clove, Garlic bulb, Mechanical properties, Textural analyzer.

Introduction

Garlic, belongs to the Alliaceae family, has been used for centuries as a culinary ingredient and for its medicinal properties. Its distinct smell and taste come from organosulfur compounds, especially allicin, which are responsible for many of its health benefits (Rodriguez, 2022). The total world production for garlic in 2023 was 28,672,225.8 metric tonnes. India is the world's second-largest producer of garlic, following China, with an annual production of 3.3 million tonnes continuing its upward trajectory. Madhya Pradesh remains the top producing state within India. Globally, China is the undisputed leader, producing well over 20 million metric tons annually, holding a market share of 70-80% (Anonymous, 2025; Chhetri *et al.*, 2024). A garlic possesses many potential health benefits. Its strong antioxidant and anti-inflammatory properties may help to reduce the risk of chronic diseases like heart disease and some cancers. Garlic also boosts the immune system and has antiviral and antibacterial effects (Ansary *et al.*, 2020). Besides allicin, other compounds in garlic, like phenolics, saponins and polysaccharides, also contribute to its health benefits. These compounds have been shown to have antimicrobial, neuroprotective and renoprotective effects (Netzel, 2020).

The rising global demand for garlic calls for efficient and scalable processing techniques. Conventional manual processing is labour-intensive, time-consuming and prone to substantial product loss and quality inconsistencies. As a result, mechanizing garlic processing such as peeling, slicing and dicing is essential to meet market demands while maintaining uniform product quality. To design and develop specialized equipment for crop production and processing, as well as to provide facilities for planting, handling, storing, drying, bulb breaking, peeling and other unit operations in garlic processing, understanding its engineering properties is essential (Manjunatha *et al.*, 2008). However, successful mechanization relies on a comprehensive understanding of garlic's physical and mechanical properties (Gupta *et al.*, 2015). Beyond its culinary uses, garlic undergoes various processing methods to enhance its shelf life, flavour and applicability in food products. Understanding the mechanical properties of garlic is crucial for optimizing these processing techniques and developing efficient mechanized systems in the food industry.

Dress 2011 reported that a study on the coefficient of friction is crucial for two primary reasons: minimizing it in certain machine parts to enhance efficiency and maximizing it in processes like rubbing where it's essential for the operation. Modern garlic processing uses specialized machines like pneumatic peelers and cylinder-concave peelers to improve efficiency and quality. The design and effectiveness of these machines depend heavily on garlic's mechanical properties, such as its crushing strength, cutting force and friction (Manjunatha *et al.*, 2014; Unal 2024). Firmness i.e. peak force is widely assessed in food, pharmaceutical, cosmetic and industrial materials to determine product quality, uniformity and suitability for intended use. It is an important textural parameter used to evaluate the mechanical resistance of a material when an external force is applied. Texture Profile Analysis (TPA) is commonly employed to assess the different attributes such as hardness and crushing strength, providing insights into how different processing methods affect the final product's texture. A texture analyser (Model TA-HDi, Stable Micro Systems, UK) was used for the evaluation of textural properties of garlic bulbs and garlic clove as shown in Fig. 1. This device consists of a moving upper section, a stable lower platform, a driving unit and a data acquisition system.

For instance, rupture and cutting forces determine the crushing strength of garlic cloves to design efficient peeling machines. Friction coefficients between garlic and different materials are also crucial for designing conveying and handling systems. Furthermore, understanding the relationship between these mechanical and textural properties is essential for minimizing product damage during processing. Kaleem *et al.* (1993) reported that the angle of repose found important in determining the inclination angle of the machine hopper tank.

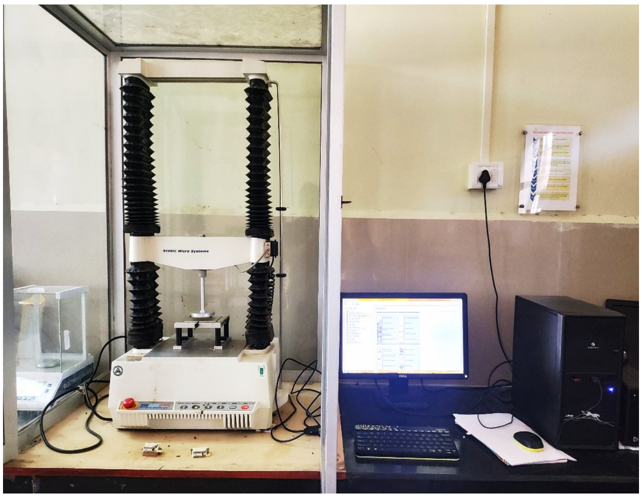

Fig. 1 : Texture analyser setup in laboratory (TA-HDi, Stable Micro Systems, UK)

Mechanical damage is one of the important factors contributing to agriculture waste during harvest and post-harvest operation (Jahanbakhshi *et al.*, 2019). In order to overcome such issues, present research focuses on characterizing the mechanical properties of garlic to optimize and modify the design and operation of garlic processing machinery, ultimately improving efficiency and minimizing product damage. This characterization will provide valuable data for engineers and food processors in developing and implementing effective mechanization strategies.

Materials and Methods

Fresh, well-matured and cured garlic bulbs of the Agrifound White (G-41) cultivar were procured from Chilli and Vegetable Research Unit, Akola, Maharashtra. Agrifound White (G-41) is a variety of garlic with compact, silvery white bulbs and creamy flesh developed by the National Horticultural Research and Development Foundation (NHRDF) and is suitable for growing in Maharashtra and Madhya Pradesh. Friction plate apparatus (Fig. 2) and angle of repose apparatus (Fig. 3) were used to determine the coefficient of friction and angle of repose, whereas garlic's textural properties were recorded using a texture analyser. The mechanical attributes of garlic bulbs and garlic cloves were determined for selected garlic samples (ten samples). The present experiment was conducted in the Department of Agricultural Process Engineering, Dr. Panjabrao Deshmukh Krishi Vidyapeeth, Akola, Maharashtra.

Mechanical properties of garlic bulbs and garlic cloves

Mechanical properties of agricultural commodities describe their behaviour under applied forces, influencing the design of harvesting, processing, handling and storage equipment (Manjunatha *et al.*, 2023; Gupta *et al.*, 2015). These properties include the coefficient of friction, angle of repose, compression force and cutting force that help in designingand modifying conveying, peeling, slicing, crushing and sorting machines (Ambrose 2020). Also, prevents mechanical damage during transportation and ensures proper force application in garlic processing. In this way, these properties are crucial for reducing post-harvest losses and improving processing efficiency in agricultural commodities.

Coefficient of friction

The coefficient of friction represents the resistance to the movement of garlic cloves and bulbs when in contact with different surfaces. It is crucial for designing storage bins, hoppers, conveyors and processing equipment. It is the resistance encountered by a material when sliding over another surface, influenced by factors such as moisture content and surface roughness (Mohsenin 1986; Manjunatha *et al.*, 2008). A tilting table/inclined plane method with an adjustable angle was used to measure the coefficient of friction (Manjunatha *et al.*, 2023). A frame made with square wooden bars was placed on the surface. The frame was filled with bulbs. For this different surfaces were used such as stainless steel (SS), mild steel (MS), glass, fiber glass and wood. The table was tilted slowly manually until the movement of the garlic bulb or clove. Then, the angle at which motion begins was recorded by the protractor and used to compute the coefficient of static friction according to equation (1) (Bahnasawy, 2007, Dress 2011 and Verma *et al.*, 2024). An average of five replications was recorded.

$$\mu = \tan(\theta) \tag{1}$$

Where,

μ = Coefficient of friction, (Dimensionless)

θ = Angle of friction, (°)

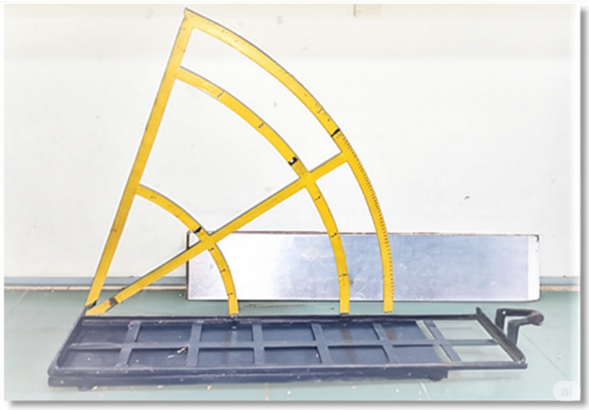

Fig. 2 : Tilting table to measure the coefficient of friction

Angle of repose

The angle of repose is an important frictional property of garlic bulbs and cloves, influencing the design of storage bins, hoppers and conveyors. It is the angle between the horizontal and the slope of a heap of granular material formed by pouring the material onto a surface (Mohsenin, 1986). It helps determine the packing and stacking behavior of garlic cloves in storage and transport, reducing losses due to spillage or crushing (Dikkar *et al.*, 2024).

Fig. 3 : Apparatus to measure the angle of repose

The angle of repose was calculated using equation (2) (Kumbhar *et al.*, 2023; Verma *et al.*, 2024 and Jadhav *et al.*, 2024),

$$\text{Angle of Repose} = \tan^{-1}\left(\frac{2h}{d}\right) \tag{2}$$

Where,

h = Height of heap, cm

d = Diameter of heap, cm

Compression force or Rupture force

The force required to break garlic bulbs is a key engineering parameter in designing harvesting, peeling, breaking and packaging machinery. Proper knowledge of this force improves efficiency, reduces mechanical losses and enhances garlic quality in commercial production and processing. In this study, a texture analyzer was employed to determine the breaking force of garlic bulbs in both vertical and horizontal orientations (Manjunatha *et al*., 2023). The rupture force is the minimum force necessary to break the sample i.e. garlic bulbs and garlic cloves. The first highest peak force recorded to break the sample is known as hardness. The texture analyzer was calibrated for weight and distance prior to conducting each test (Sonwani *et al*., 2024). Compression testing involves the use of probes that should be of equal (throughout the test) or greater surface area than the sample. For compressive force measurement, the garlic bulb or clove was placed on the stable lower platform and compressed using the moving upper probe (P/75-75 mm aluminum platen cylinder probe) (Ambrose 2020) at a loading rate of 0.5 mm/sec (Manjunatha, 2008). For individual cloves, the test is similar but involves placing a single clove on the platform and compressing it until deformation or rupture occurs. The Texture Analyzer was interfaced with a computer to enable real-time recording of the force-deformation curve. The peak force recorded represents the hardness of the garlic bulb and clove.

Fig. 4 : Force required to break the garlic bulb using a texture analyzer

Cutting force

Cutting refers to the minimum force required to cut the garlic bulb and also the garlic clove without causing damage. It is a key mechanical property used in designing garlic processing machines (Dress, 2011). It is the most common test mode used to assess the cutting or shearing force required to penetrate or slice a material. The same procedure was applied for shear force measurement, except the probe was replaced with a Warner-Bratzler blade. 1-2 mm/sec is common for the pre-test phase to ensure the probe aligns gently with the material before cutting. Test speed between 2-3 mm/sec for materials like garlic which ensures that the material is cut with minimal damage and the force is measured accurately. Post-test speed of 1 mm/sec is a common setting for retraction after the test to avoid additional forces or damage to the sample. Fig. 5 and Fig. 6 shows the cutting force determination using texture analyser.

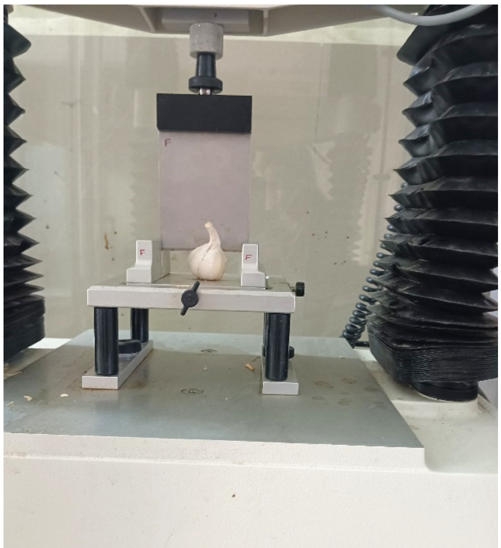

Fig. 5 : Cutting force or shear force determination using texture analyzer for garlic bulb

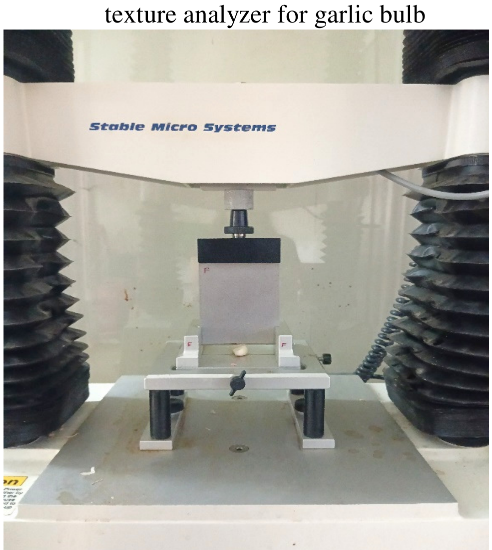

Fig. 6 : Cutting force or shear force determination using texture analyzer for garlic clove

Result and Discussion

A required quantity of whole garlic bulbs and cloves was selected to determine their mechanical properties. These properties vary significantly among different garlic varieties, influencing their usability and market value. This section discusses the results obtained in the present investigation in relation to previous research findings.

The coefficient of friction plays a vital role in designing efficient garlic processing and handling machinery. By understanding the coefficient of friction of garlic on different materials, engineers can optimize the design of these systems to improve efficiency, reduce damage and enhance overall performance. The static coefficient of friction varied on six different surfaces for garlic bulbs, ranging from 0.48 to 0.55 with a mean value of 0.51 ± 0.02 on wood (μ_w), on glass varied from 0.21 to 0.28 with a mean value of 0.24 ± 0.02 (μ_g), on stainless steel ranged from 0.29 to 0.38 with the mean value of 0.33 ± 0.03 (μ_{ss}), on fiber glass from 0.42 to 0.55 with the mean value of 0.48 ± 0.04 (μ_f) whereas on mild steel ranging from 0.40 to 0.47 with the mean value of 0.43 ± 0.02 (μ_{ms}). In the case of the garlic clove, the static coefficient of friction ranged from 0.50 to 0.58 with a mean value of 0.54 ± 0.03 on wood (μ_w), on glass ranged from 0.23 to 0.30 with a mean value of 0.27 ± 0.02 (μ_g), ranged from 0.32 to 0.40 with the mean value of 0.35 ± 0.03 on stainless steel (μ_{ss}), from 0.46 to 0.57 with the mean value of 0.50 ± 0.04 on fiber glass (μ_f) and on mild steel varied between 0.42 to 0.50 with the mean value of 0.46 ± 0.02 (μ_{ms}). Fig. 7 shows the variation for the coefficient of friction between garlic bulb and garlic clove on selected testing surfaces.

Manjunatha *et al.* (2008) measured the coefficient of friction for garlic segment which align closely with reported range for wood (0.46–0.53) and mild steel (0.34–0.41). The coefficient of friction of bulb and clove on various surfaces showed that static friction on wood was higher than on the other surfaces, which may be due to the roughness of the surface and static friction on glass is the lowest due to its smoothness and polished surface (Manjunatha *et al.*, 2023). But SS can be preferred for designing garlic processing machinery due to its high corrosion resistance, hygienic cleanability, mechanical durability, non-reactive and sanitary standards according to industry standard for food processing machinery and also due to its low coefficient of friction (Unal, 2024).

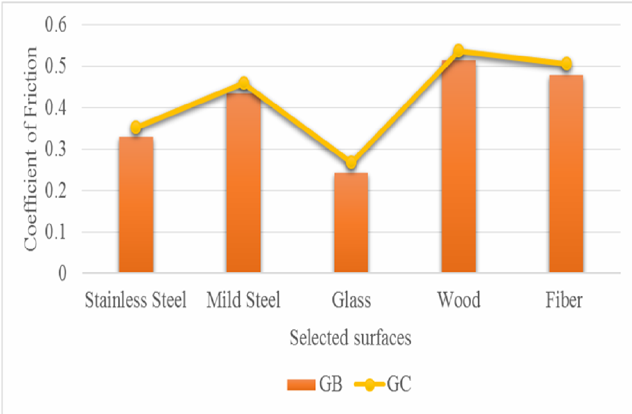

Fig. 7 : Variation for the coefficient of friction between garlic bulb and garlic clove

Table 1 and Table 2 shows the maximum, minimum, average values with standard deviation and coefficient of variance of garlic bulb and garlic clove for the coefficient of friction on selected surfaces and angle of repose, respectively.

Table 1 : Statistical analysis for coefficient of friction of garlic bulb and garlic clove

Testing surfaces	Coefficient of Friction									
	Maximum		Minimum		Average		SD		CV (%)	
	GB	GC	GB	GC	GB	GC	GB	GC	GB	GC
Stainless Steel (μ_{ss})	0.38	0.40	0.29	0.32	0.33	0.35	0.03	0.03	8.46	7.18
Mild Steel (μ_{ms})	0.47	0.50	0.40	0.42	0.43	0.46	0.02	0.02	4.58	5.14
Glass (μ_g)	0.28	0.30	0.21	0.23	0.24	0.27	0.02	0.02	8.33	7.80
Wood (μ_w)	0.57	0.58	0.48	0.50	0.51	0.54	0.02	0.03	4.83	4.97
Fiberglass (μ_f)	0.55	0.57	0.42	0.46	0.48	0.50	0.04	0.04	8.04	7.22

SD-Standard Deviation; CV-Coefficient of Variation; GB-Garlic Bulb and GC-Garlic clove.

The angle of repose influences the capacity of the storage structure and the inclination needed for the material to flow smoothly. It must be greater than its maximum value, which helps to determine the slope of the tank bottom. Angle of repose is higher for cohesive material. In the present study, the average value of the angle of repose for garlic clove and garlic bulb was calculated as 46.70° ± 1.97° and 40.70° ± 2.04°, respectively (Table 2). Kumbhar *et al.*, (2023) were also reported the angle of repose of garlic clove was

41.37° ± 1.48°, which was comparable with the obtained value. According to Bahnasawy (2007), the angle of repose ranges from 42.65° to 44.15° for garlic bulbs, which is also similar to the results obtained in the present investigation. Fig. 8 depicts the variation for the angle of repose between garlic bulb and garlic clove.

Table 2 : Statistical analysis for an angle of repose

Parameters	Angle of repose (°)	
	Garlic clove	Garlic bulb
Maximum	49.72	44.42
Minimum	43.83	37.95
Average	46.70	40.70
Standard Deviation (SD)	1.97	2.04
Coefficient of Variation (%)	4.21	5.02

It was also observed that the angle of repose of cloves was higher than that of bulbs (Figure 7), which follows the trend reported by Dress 2011. A material with a low angle of repose creates flatter piles compared to one with a high angle of repose.

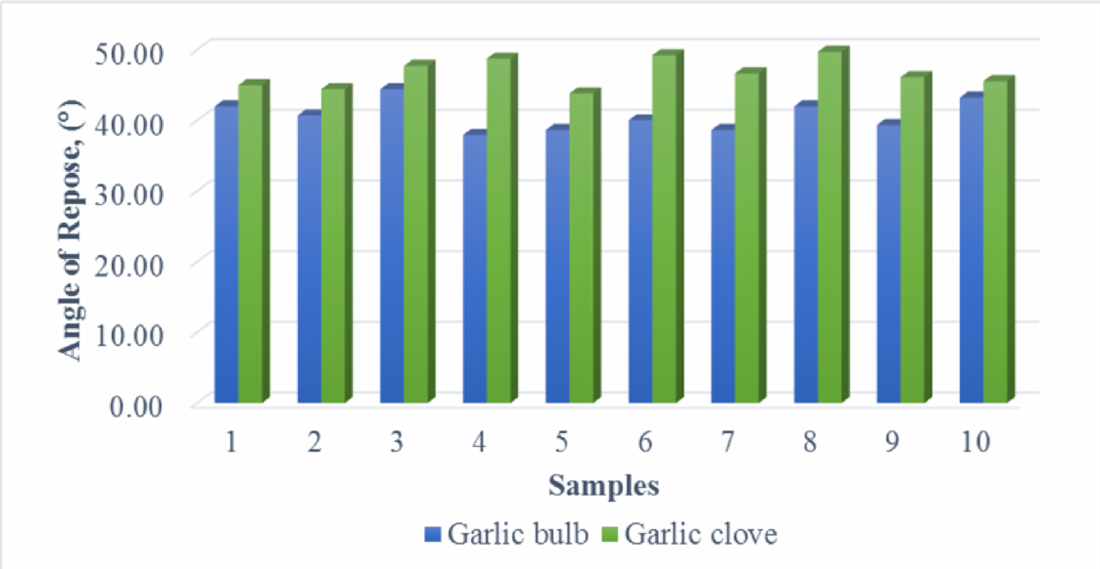

Fig. 8 : Comparison between garlic bulbs and garlic cloves for the angle of repose

Compression force play important in garlic bulb disintegration, garlic peeling, garlic powder making, physical damage and material resistance (Singh *et al.*, 2022). In the present study, results show that the rupture force/compression force for garlic bulb in vertical position ranged between 80 N to 110 N, whereas in horizontal position ranged between 40 N to 65 N. The force required to loosen the cloves from a whole bulb in the vertical position is higher than in the horizontal position, which is in agreement with the results reported by Bahnasawy (2007) for large sized bulbs. This may be due to the presence of a woody structure in the centre of the garlic bulb, which increases the force needed for clove separation in this position. The hardness of garlic bulb reported by Bahnasawy (2007) was between 110 ± 20.4 to 272 ± 25.8 N on horizontal position whereas 101 ± 9.36 to 320 ± 62.20 N on the vertical position, which influences the handling and processing behaviour of garlic. The crushing load for garlic clove ranged between 55.6 to 155.0 N (Bahnasawy, 2007). Higher force values indicate firmer and denser garlic, whereas lower force values suggest softer garlic, possibly due to ageing, moisture loss or degradation.

The force–time graph i.e. Fig. 9 and Fig. 10 determined using texture analyser for the garlic sample in vertical and horizontal orientation under uniaxial compression, respectively. Vertical orientation shows a peak force of approximately ~93.49 N (9533 g), which represents the maximum compressive resistance offered by the garlic tissue, indicating its firmness and mechanical integrity. The presence of secondary force peaks specifies multi-stage structural collapse, possibly due to the layered nature of garlic cloves. The gradual decline post-peak confirms material softening and progressive deformation. Horizontal orientation indicates peak compressive force of ~52 N, indicating significant resistance due to multiple cloves aligned across the compression axis. Horizontal positioning increases surface contact area and leads to progressive clove failure, which is evident from post-peak force fluctuations. These results are essential for the design of peeling, slicing, pressing or crushing mechanisms, ensuring optimized force application without excessive mechanical damage. The compression curve (Figure 11) for the garlic clove shows a peak resistance of approximately 28.05±10 N, confirming the clove's structural integrity prior to rupture. Bahnasawy (2007) reported average crushing load for small-sized garlic cloves as 55.60±17 N, which is higher than reported in the present study, which may due to variation in variety. The steep force increase indicates firm outer tissue, while the rapid decline post-peak reveals brittle rupture characteristics. Such data are essential in designing clove-crushing or compression-based processing units to optimize applied force and avoid over-compression or clove fragmentation.

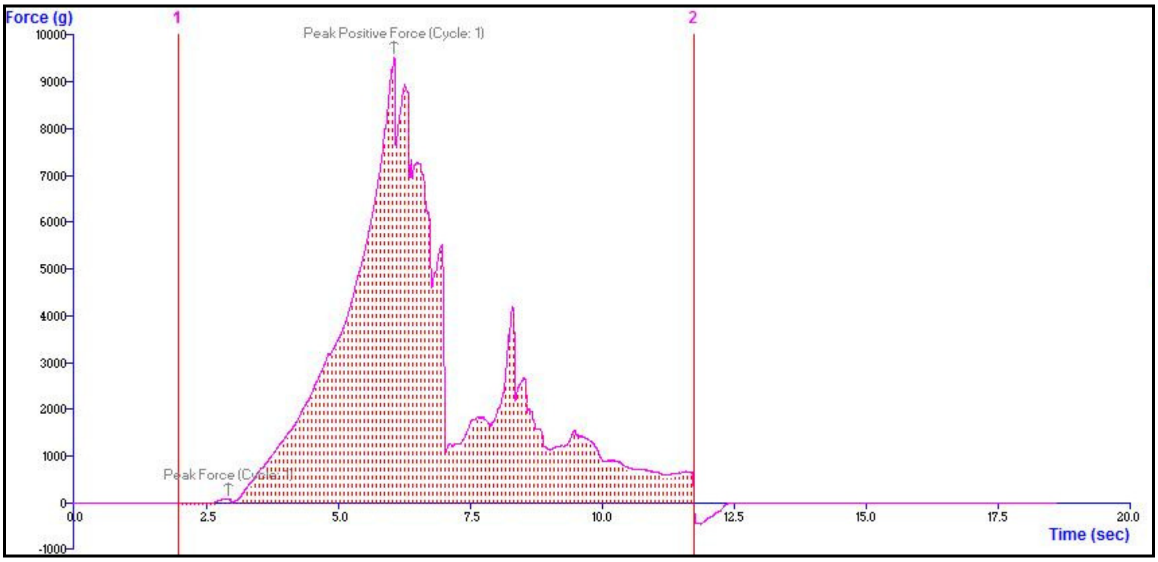

Fig. 9 : Compression test curve for garlic bulb in vertical position

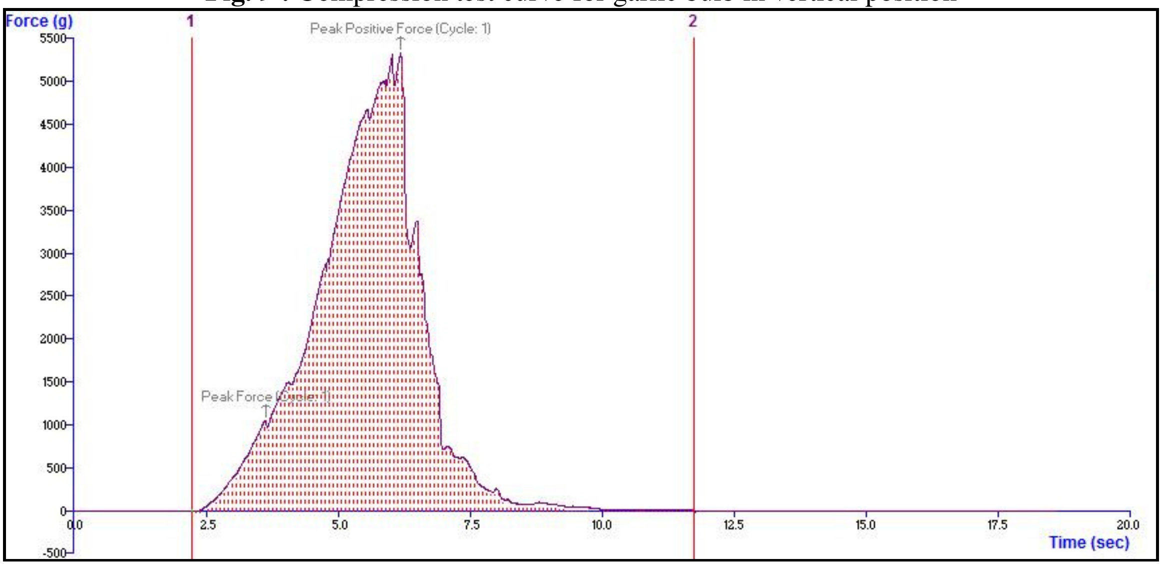

Fig. 10 : Compression test curve for garlic bulb in Horizontal position

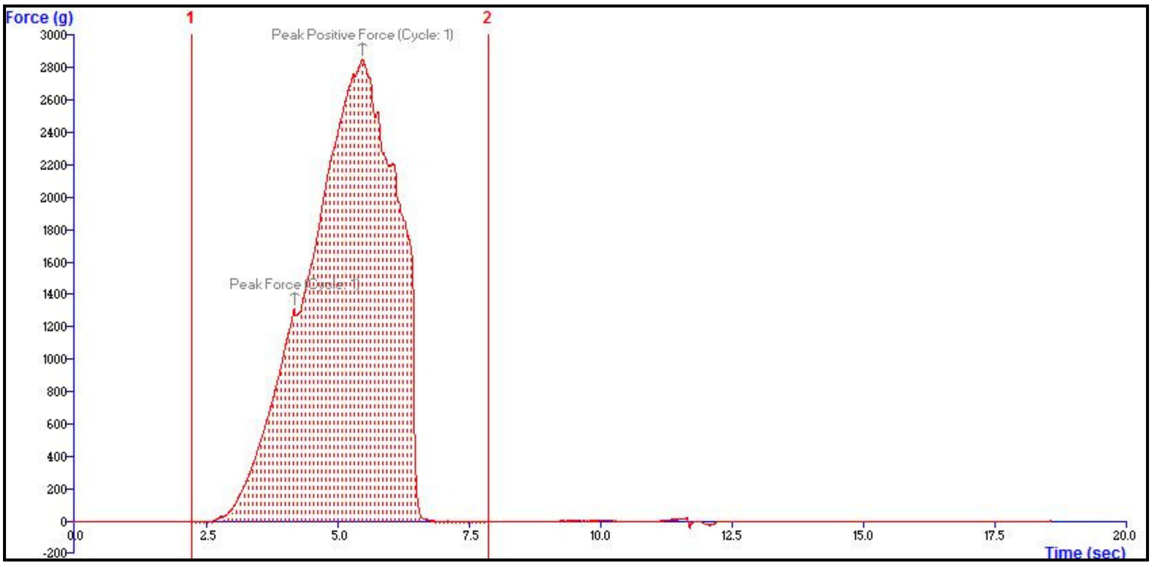

Fig. 11 : Compression test curve for garlic clove

In the present study, the cutting force for garlic bulbs were ranged from 25 N – 55 N and 15 N – 25 N for garlic clove. Force–Time curve (Fig. 12 and Fig. 13) representing the cutting test curve of a garlic bulb and garlic clove, respectively. For garlic bulb dual peaks reflect layered resistance from outer clove layers and central core. The first peak is attributed to the compression and cutting of the outer cloves, while the second peak corresponds to the central inner core. The rapid force drop following the peaks confirms a complete structural rupture. This behaviour is critical in the design of cutting blades and mechanical harvesters to ensure clean cuts with minimal energy expenditure. The force-time graph for the garlic clove cutting test shows a peak cutting force of ~18.52 N (1889.12 g), which is in alignment with the result (22.69 N) reported by Unal (2025) for garlic clove and falling within the expected range for fresh garlic tissue. The steep rise and sharp decline in force represent typical cutting behavior of soft horticultural produce. This indicates the typical mechanical response of garlic tissue, where force builds due to increasing resistance until the outer layers rupture, after which the internal tissues offer minimal resistance. These findings are helpful in optimizing blade design, sharpness and actuation force for garlic clove slicing equipment, ensuring minimal mechanical damage and energy efficiency in automated garlic processing machinery. According to Khambe *et al.*, 2025 cutting resistance of the garlic plant increased from 218.40 N - 268.60 N. Likewise, Khanpara *et al.*, 2025 employed texture analyser to separate onion leaves from the bulbs and reported cutting force range as 54.00 N to 89.78 N.

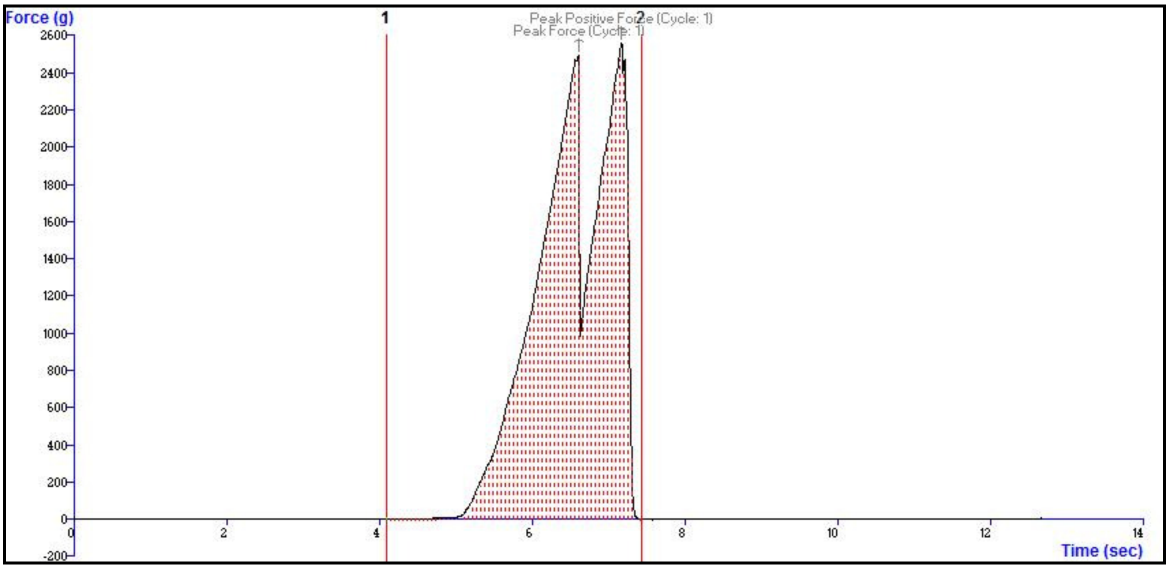

Fig. 12 : Cutting test curve for garlic bulb

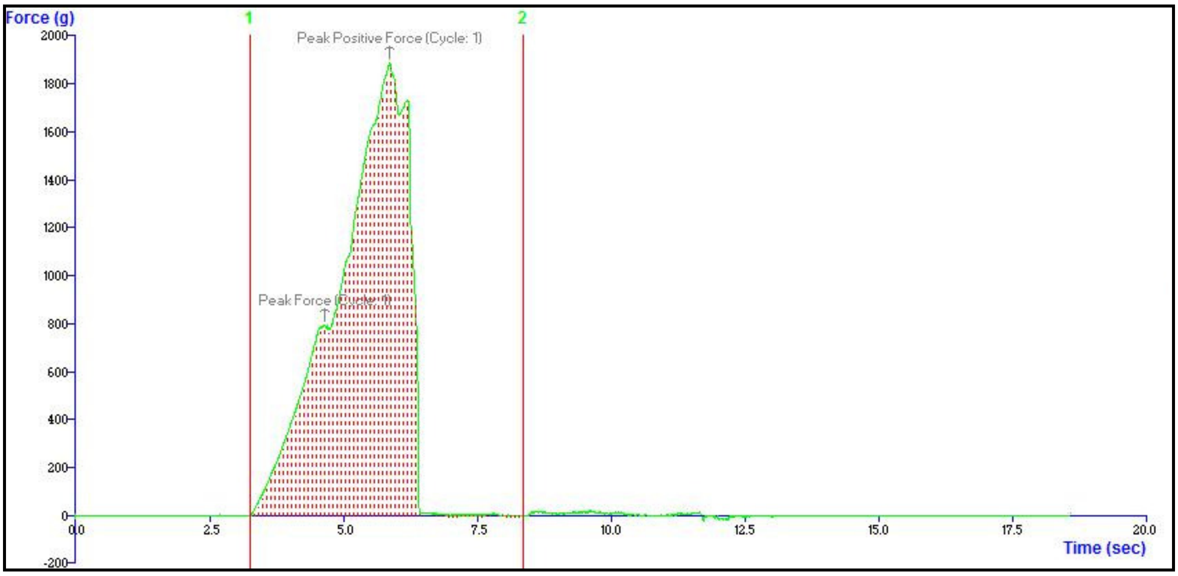

Fig. 13 : Cutting test curve for garlic clove

Conclusion

This study successfully characterized the key mechanical properties of garlic bulbs and garlic cloves essential for optimizing mechanized processing equipment. The determined compression forces (93.49 N and 52 N in vertical and horizontal orientations respectively), angle of repose values (46.70° ± 1.97° for bulbs and 40.70° ± 2.04° for cloves), and coefficient of friction (0.33 ± 0.03 for bulbs and 0.35 ± 0.03 for cloves on stainless steel) provide critical design parameters for food processing machinery. The low friction values on stainless steel surface render it ideal for hygienic processing equipment design. The cutting force data (35.67 N for bulbs and 18.52 N for cloves) and compression characteristics reveal the distinct layered resistance patterns influencing peeling, slicing and crushing operations. These quantitative findings enable engineers to optimize machine design, minimize mechanical damage, reduce post-harvest losses and maintain product quality during automated garlic processing operations. The characterized properties serve as fundamental reference data for developing efficient mechanization strategies in commercial garlic processing.

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