



Optimization of Blade Geometry and its Orientation based on Piercing Force for Debarking Jigat Trees

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ABSTRACT

Background: Jigat bark is a key important binding material in the agarbatti industry owing to its excellent adhesive property. However, owing to lack of mechanization, debarking is still mostly performed by manual operation, increasing human effort and decreasing the overall output. To support the design of a mechanized debarking machine, this study examined the effects of rake angle and blade thickness on piercing force, insertion depth and overall debarking efficiency.

Methods: The experiments were conducted with the help of piercing force setup, it consisting of an S-type load cell, chisel, bark gauge/steel ruler and digital indicator with four rake angles (30°, 40°, 50° and 90°) and three blade thicknesses (1, 2 and 3 mm).

Result: Two-way analysis of variance showed that the rake angle significantly influenced the piercing force [$F(3,48) = 19.45$, $p = 2.16 \times 10^{-8}$] and insertion depth [$F(3,48) = 74.95$, $p = 3.95 \times 10^{-18}$]. The blade thickness also significantly affected the piercing force [$F(2,48) = 3.68$, $p = 0.0327$] and insertion depth [$F(2,48) = 4.60$, $p = 0.0149$]. No significant interactions were detected during the evaluation, suggesting that both variables functioned independently. According to the regression analysis, observed that piercing force increased with blade thickness ($c = 0.467$, $p = 0.015$) and rake angle ($b = 0.443$, $p = 0.039$). The force-normalized insertion compliance ($\eta = D/F$) declined as the thickness of the blade increased ($c = -0.79$, $p = 0.013$). Bark's hardness was measured at 490 N, 50% compression and 5 mm penetration and its average moisture content was 58.4%. For practical debarking, a 2 mm blade was chosen because it was more durability and better suited for repeated impact, even though a 1 mm blade with a 40° rake angle needed less piercing force.

Key words: Agarbatti, Blade thickness, Debarking machine, Jigat, Load cell, Piercing force, Rake angle.

INTRODUCTION

Jigat (*Litsea glutinosa*) is a dioecious tree of significant industrial importance, especially for its bark, which is widely used in the agarbatti (incense stick) industry owing to its excellent binding properties (Praveena *et al.*, 2023). This species occurs in both distinct male and female forms, which is locally known as *Kollamavu* and *Uravu*, respectively. The tree can grow up to 27 m in height, with trunk diameters reaching nearly 3 m and a bole length of approximately 7.5 m. *Litsea glutinosa* is distributed across several regions of India, Sri Lanka and other parts of Asia and is well recognized for its botanical and economic value (Kirtikar and Basu, 1999; Jamaddar *et al.*, 2022).

The bark of the Jigat tree is highly valued for industrial purposes. Its mucilaginous nature has long served as a natural adhesive. According to Yoko *et al.* (2000), the primary component of Jigat bark mucilage is heteropolysaccharide polyuronides, which are generated from the cell wall's sugars and uronic acids. They readily absorb moisture, expand and create gel-like masses. These materials have the strong binding properties necessary to make incense sticks.

The structural and physical properties of Jigat bark significantly affect its processing behaviour. The inner layer of the bark appeared light reddish-brown, while the outer layer was brown. Typically, the bark is cut into flat or slightly curved strips that are 18-20 cm long, 7-8 cm wide and 1.5-3 cm thick (Kulkarni *et al.*, 2011).

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Jigat bark, like the majority of biological materials, has anisotropic mechanical behavior, which means that the direction of loading affects its mechanical characteristics. Ran *et al.* (2022) conducted studies and reported that directional dependency in jujube bark indicates that anisotropy plays a major role in the effectiveness of cutting and peeling operations in bark materials.

Previous studies have demonstrated that the rake angle significantly influences the cutting efficiency. Caceres *et al.* (2018) reported that a rake angle of 40° reduced cutting forces and improved surface quality during wood processing. Dvoracek *et al.* (2022) conducted studies on reliable models and predicted hardwood cutting forces. Jiang *et al.* (2022) reported that the rake angle and depth of cut significantly affect surface roughness and cutting force, while cutting speed mainly affects cutting force; the rake angle is the most significant element.

Wilmar Hernandez (2006) studied and reported on how adaptive filtering can increase the accuracy of strain-gauge load cells; testing is done to detect force in car seats. Joo *et al.* (2002) studied FEM-optimized multi-component load cells that provide accurate and reliable force and moment measurements with low coupling errors.

In addition to cutting quality, energy consumption is a key parameter of machine efficiency. Xu *et al.* (2022) reported on the effects of rake angle, depth of cut, cutting speed and tool wear on cutting power and observed that the rake angle had a significant effect on power consumption.

This study presents a preliminary investigation of the piercing force and examines the effects of blade thickness and rake angle on blade geometry optimization using a specially developed experimental field setup. This study aimed to identify scientifically optimized blade parameters and operating conditions that minimize the piercing force and power consumption while enhancing debarking efficiency and machine productivity, thereby supporting the development of energy-efficient mechanical debarking for the Jigat tree.

MATERIALS AND METHODS

Geographical location

The experimental studies were conducted at the campus nursery of the Kerala Forest Research Institute (KFRI), Peechi, Kerala, in South India, during the period 2025-2026. KFRI is situated approximately 20 km east of the Thrissur district and encompasses 28 ha of reserved forest next to the Peechi-Vazhani Wildlife Sanctuary in Kerala, India. The institute is located at 10.530°N latitude and 76.347°E longitude, at an altitude of 186 m above sea level.

Field technique for bark thickness measurement by bark gauge

The bark gauge (Fig 1) is a simple tool used to measure tree bark thickness without damaging the cambium (Laasasenaho *et al.*, 2005). This enables the direct measurement of bark thickness under field conditions with minimal effort. It consists of a pointed probe and a graded scale of up to 50 mm.

Laboratory test for bark hardness test

A laboratory test was conducted using a texture analyzer (Fig 2) and the hardness of the bark was determined using the standard procedure for wood outlined in IS 1708.

Throughout the test, the load was applied consistently and the movable head of the machine was maintained at a constant travel speed of 6 mm/min.

Development of experimental setup for measuring piercing force

A field-based experimental setup was fabricated using a chisel, load cell, digital indicator and bark gauge to assess the force required to pierce the bark by varying the rake angle. An S-type load cell (Fig 3) with a 50 kg capacity and appropriate mounting system was used. Model 20210 is an accurate and adaptable load cell that is ideal for measuring suspended loads, universal testing machines, process control, machine automation and in-line tension assessment. Its construction from high-tensile tool steel ensures durability and reliable operation in demanding



Fig 1: Bark gauge.

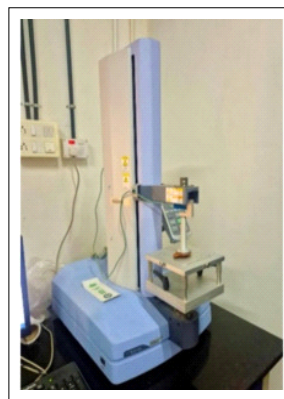


Fig 2: Texture analyzer.



Fig 3: S-type load cell.

industrial environments. Based on the strain gauge principle, the load cell provided full temperature correction between 10°C and 50°C. The technical characteristics of the load cell used in this study are listed in Table 1.

Using a cable connection, a digital meter (Fig 4) with a 50 kg maximum capacity and RS232 output was used to collect the load cell measurements. In addition to displaying the weight in kilograms, it has a charging connector, power switch and reset button to ensure precise and reliable operation.

A metal frame was constructed based on the tree's GBH using L-angle iron, cable ties and a flat plate. With the use of nuts and bolts to ensure sturdy support, the arrangement was firmly fastened around the tree trunk using a cable tie (Fig 5). To guarantee adequate chisel insertion and transfer the impact, an extension rod was fastened to a chisel positioned perpendicular to the tree trunk and immediately connected to an S-type load cell. The chisel could be positioned at different rake angles using an adjustable extension arm.

T_1 (1 mm), T_2 (2 mm) and T_3 (3 mm) blade thicknesses (Fig 6) were assessed at 30°, 40°, 50° and 90° rake angles (Fig 7). A digital meter was used to measure the manually applied load for each rake angle and blade configuration. A digital indicator and steel ruler or bark gauge were used to determine the force needed for piercing and the appropriate depth of operation. This setup (Fig 8) allowed us to evaluate the cutting performance and enabled precise measurement of the force required to insert the bark.

Statistical analysis

We investigated the use of statistical and computational methods to examine the effects of blade thickness and rake angle on the piercing force and insertion depth. Four rake angle levels (30°, 40°, 50° and 90°) and three blade thicknesses (1, 2 and 3 mm) were used in this experiment. A total of 60 observations were obtained from five tests for each combination. This made it possible to compare in detail the impact of various blade geometries on performance.

To study the effects, a two-way ANOVA was used to compare the effects of blade thickness and rake angle separately and together. Interaction plots were used to visually assess if the impact of one element was reliant on the level of another. Before interpreting the data, the ANOVA assumptions were verified using normality and variance tests, as well as residual plots.

In order to handle the nonlinear interactions between the blade geometry and piercing force, the piercing force was estimated as a function of the rake angle and thickness using power-law regression. The mechanical energy required to remove bark was calculated by multiplying the force by the insertion depth and the insertion depth was standardized by force in order to assess cutting efficiency. Pareto analysis was used to determine which blade designs provided the best balance between piercing force, insertion depth and energy consumption. All analyses were performed

Table 1: Technical specifications of the load cell.

Item	Specification
Excitation voltage	10 VDC-Maximum 15 VDC
Nominal output	3.0 mV/V
Non-linearity	< ±0.025% FSO
Hysteresis	< ±0.02% FSO
Non-repeatability	< ±0.01% FSO
Safe overload of rated capacity	150%



Fig 4: Digital indicator.

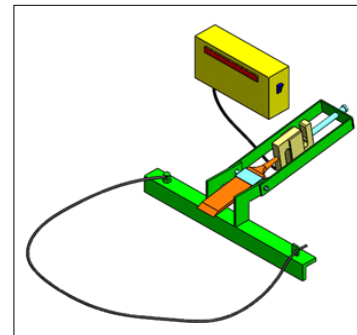


Fig 5: 3D model.

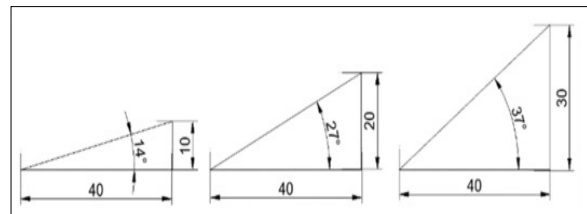


Fig 6: Piercing-edge dimensions of each blade (mm).

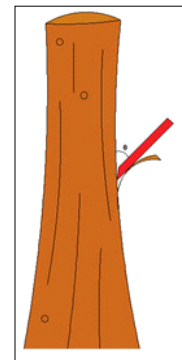


Fig 7: The rake angle of the cutting blade.

using the Python packages NumPy, Pandas, SciPy, Statsmodels, Matplotlib and Seaborn and they were then cross-checked using R.

RESULTS AND DISCUSSION

Impact of rake angle and blade thickness on piercing force

Table 2 displays the results of a two-way analysis of variance (ANOVA) conducted to determine the effects of rake angle and blade thickness on piercing force. Using preliminary diagnostic tests, we validated the assumptions of variance homogeneity and normality. The ANOVA data shows that rake angle has a substantial effect on piercing force [$F(3,48) = 19.45$, $p = 2.16 \times 10^{-8}$], indicating its sensitivity to rake angle fluctuations. The effect of blade thickness was also significant [$F(2, 48) = 3.68$, $p = 0.0327$], indicating that thickness variations influenced cutting resistance. The relationship between rake angle and blade thickness, on the other hand, was not statistically significant [$F(6, 48) = 1.98$, $p = 0.0877$], indicating that the impact of rake angle on piercing force is relatively constant over the range of examined blade thicknesses.

The interaction plots (Fig 1a) provide additional support for these conclusions. This demonstrates a general increase in the piercing force with an increase in the rake angle for all

blade thickness levels. Although thicker blades tended to require higher piercing forces, especially at larger rake angles, this pattern indicates an increasing main-effect contribution of blade thickness rather than a major interaction effect. For post-hoc pairwise comparisons, Tukey's HSD test was used to confirm the significant differences between the rake angle values. According to Caceres *et al.* (2018), the finest surface finish and the lowest cutting forces were obtained at a 40° rake angle. The findings demonstrate that the rake angle has the greatest effect on the insertion depth, peaking at 40° and providing an ideal balance between shear stress and friction. Thinner blades can insert deeper because they concentrate the tension at the piercing edge and reduce the resistance. The rake angle and blade thickness did not significantly interact; therefore, each can be modified separately.

Insertion depth response

The effects of rake angle and blade thickness on insertion depth were investigated using two-way ANOVA. The results indicate that insertion is primarily controlled by changes in rake angle, as the rake angle had a significant effect on insertion depth [$F(3,48) = 74.95$, $p = 3.95 \times 10^{-18}$].

Blade thickness also had a significant effect on insertion depth [$F(2,48) = 4.60$, $p = 0.0149$], confirming that thickness plays a role in determining how deeply the blade inserts the material. However, no significant interaction was observed between the rake angle and blade thickness [$F(6,48) = 1.69$, $p = 0.145$]. This suggests that the effect of the rake angle on the insertion depth remains largely the same for all the blade thicknesses considered in this study.

Power-law model and validation of piercing force

The nonlinear relationship between piercing force and blade geometry was represented by a power-law regression and structural compliance was defined as depth per unit of force. To assess the impact of blade geometry on piercing force, we employed a power-law regression model. In this model, t is the blade thickness (mm), α is the rake angle ($^\circ$), F is the piercing force (N) and k , b and c are constants calculated from the data (Fig 9).

$$F = k \alpha^b t^c$$



Fig 8: Developed field setup for measuring piercing force for the jigat tree.

Table 2: Piercing force and insertion depth were analyzed using two-way ANOVA.

Response variable	Source	Sum of squares	df	F-value	p-value
Piercing force (N)	Blade thickness	130.48	2	3.68	0.0327
	Rake angle	1035.41	3	19.45	2.16×10^{-8}
	Thickness $\times$ angle	210.39	6	1.98	0.0877
	Residual	851.84	48	-	-
Insertion depth (mm)	Blade thickness	37.22	2	4.60	0.0149
	Rake angle	909.68	3	74.95	3.95×10^{-18}
	Thickness $\times$ angle	40.92	6	1.69	0.1450
	Residual	194.20	48	-	-

*Significant at $P < 0.05$.

Where,

F= Piercing force.

α = Rake angle.

t= Blade thickness in the model.

These predictors explain a large amount of the variability in the piercing force, as evidenced by the statistically significant power-law regression model for the piercing force that was obtained (overall model $F = 5.36$, $p = 0.007$). The model was affected by both the rake angle and blade thickness. The piercing force was positively affected by the blade thickness ($c = 0.467$, $p = 0.015$) and the rake angle also made a substantial contribution ($b = 0.443$, $p = 0.039$). These results indicate that increases in either the blade thickness or rake angle lead to higher piercing forces.

The diagnostic plots (Fig 10) support the adequacy of the power-law formulation, showing approximately constant variance of residuals, near-normal residual distributions and

no evidence of influential outliers or systematic patterns. Collectively, these diagnostics confirm that the fitted model provides an appropriate representation of experimental data.

Force normalized insertion compliance

Structural compliance was defined as the insertion depth by the piercing force and expressed in mm/N.

A nonlinear power-law model of the form:

$$\eta = a \alpha^b t^c$$

Revealed a statistically significant negative exponent for blade thickness ($c = -0.79$, $p = 0.013$), indicating that the insertion effectiveness decreases monotonically with increasing blade thickness. In contrast, the exponent associated with the rake angle was not statistically significant, suggesting that when the piercing force is considered in the efficiency metric, the rake angle primarily

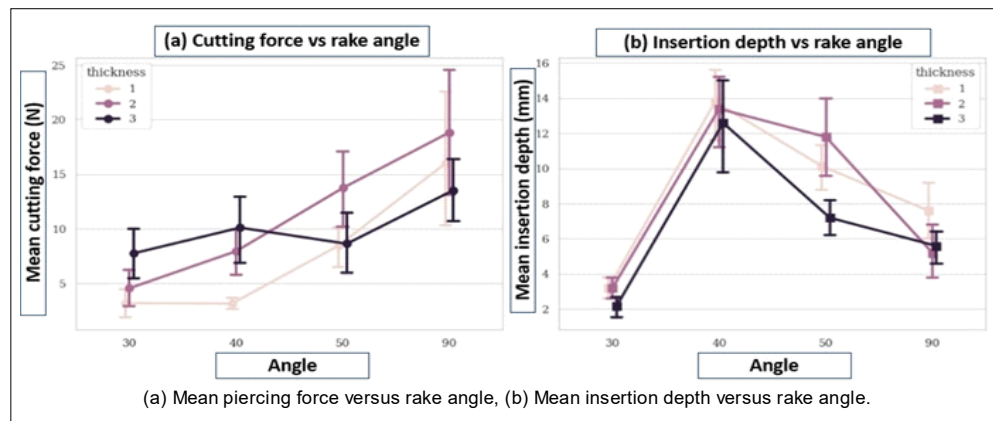


Fig 9: Interaction effect of blade thickness and rake angle.

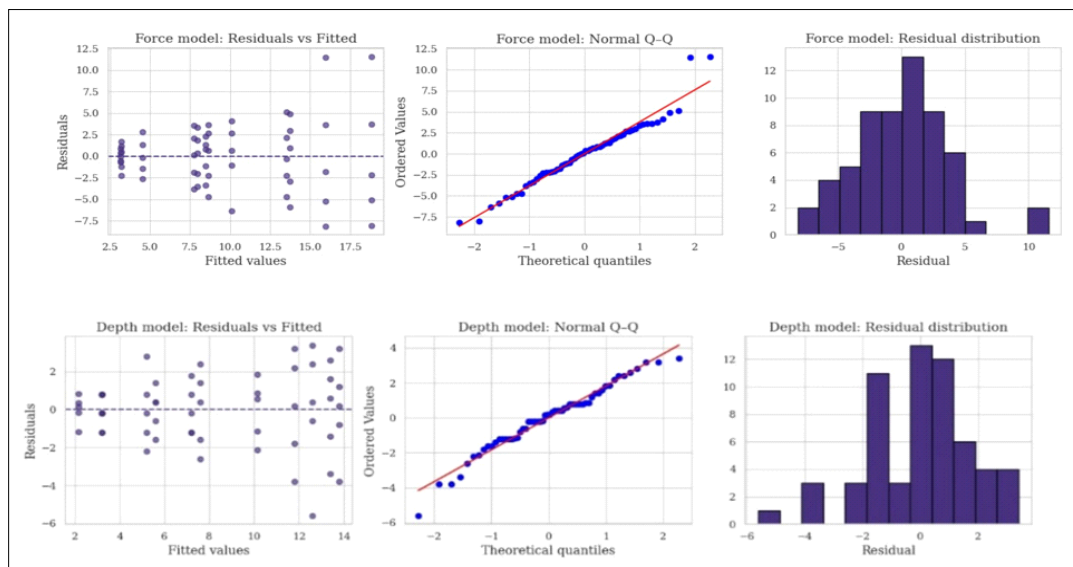


Fig 10: The residuals vs fitted values, normal Q-Q plot, residual distribution diagnostic plots for the piercing force and depth power-law model.

influences the magnitude of the force rather than the overall structural compliance. The force-normalized structural compliance (Fig 11) shows that a higher blade thickness leads to decreased structural compliance because of increased frictional losses, whereas thinner blades are better at turning the applied force into effective cutting.

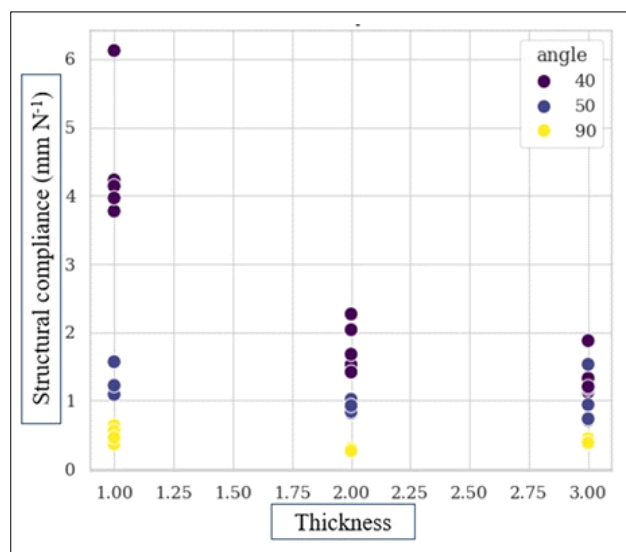


Fig 11: Structural compliance as a function of blade thickness with a fitted power-law curve.

Multi-objective optimization and pareto-optimal solutions

The multi-objective optimization showed that the piercing force and insertion depth were balanced, suggesting that the choice of blade should consider the overall structural compliance rather than only optimizing insertion or limiting force. The force-depth trade-off (Fig 11) revealed a well-defined Pareto front concentrated in the region of low piercing force and moderate-to-high insertion depths.

The configurations are summarized in Table 3. The Pareto set is dominated by a 1 mm blade thickness, particularly at rake angles of 40° and 50°, confirming the robustness of thin-blade configurations.

Performance at extreme rake angle (90°)

The relationship between the piercing force and penetration depth at a rake angle of 90° is shown in Fig 12. Excessively high piercing forces were linked to moderate penetration depths, suggesting that compression dominated deformation more often than efficient piercing. Significant energy loss results from this mechanical inefficiency at very high rake angles, emphasizing the necessity of carefully selecting the blade angles.

Ranking of blade thickness and rake angle

The average performance measures for the different blade thicknesses are given in Table 4. Finally, the performance evaluation showed that 1 mm blade thickness offered a piercing force with the highest insertion compliance.

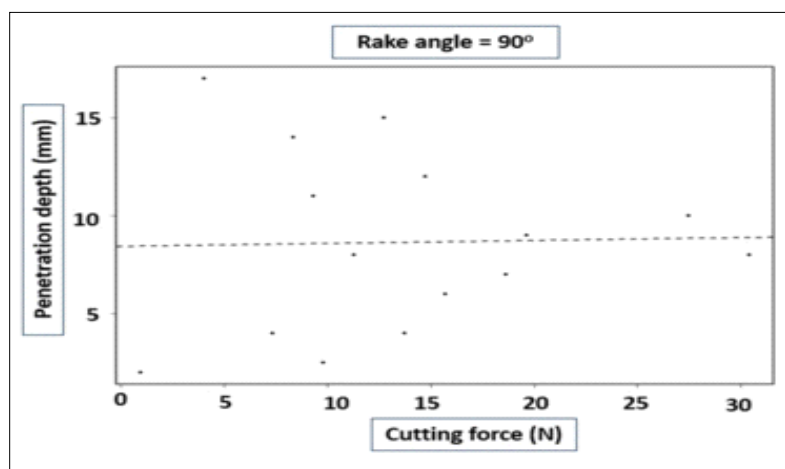


Fig 12: Piercing force at a rake angle of 90° with respect to the penetration depth.

Table 3: Pareto-optimal blade-rake angle configurations.

Thickness (mm)	Angle (°)	Force (N)	Depth (mm)	Structural compliance (mm N ⁻¹)	Energy (Nmm) (FD)
1	40	2.65	10	3.77	26.50
1	50	2.45	15	6.12	36.75
1	90	4.02	17	4.23	68.34
3	30	3.73	7	1.88	26.11
3	50	3.92	6	1.53	23.52

Table 4: Blade thickness ranking based on piercing force, insertion depth and structural compliance.

Thickness (mm)	Mean insertion depth (mm)	Mean piercing force (N)	Structural compliance (mm N ⁻¹)
1	8.68	7.70	1.85
2	8.40	11.30	0.931
3	6.89	10.00	0.745

Table 5: Rake angle ranking under optimal insertion conditions.

Rake angle (°)	Mean insertion depth (mm)	Mean piercing force (N)	Structural compliance (mm N ⁻¹)
40	13.2	7.06	2.5
50	9.71	10.28	1.01
90	6.13	16.12	0.4

Even the 3 mm blade demanded virtually less force than the 2 mm blade, the average of the studies influenced the outcome. The opposite was observed in several tests with the 3 mm blades, which needed more effort, further emphasizing the resistance faced in actual cases. Overall, it was inferior to due much lower insertion and effectiveness.

Table 5 presents the ranking of rake angles deemed most effective after adding a condition (mean insertion depth ≥ 7.5 mm). Hence, rake angles that resulted in mean insertion depths of 7.5 mm and above were found effective in practice for the removal of the bark. Consequently, the 40° rake angle generated the most appropriate depth of penetration that required the least amount of piercing force. This means that there is a need to optimize the angle of the blade to optimize the productivity and energy conservation capacity of the bark removal process.

Final synthesis

Tool geometry selection cannot be based solely on piercing force or insertion depth, as shown by the combined ANOVA, regression modeling, efficiency analysis and Pareto optimization. The force-normalized insertion compliance and multi-objective superiority provide a strong basis for evaluation. The selection sequences were as follows:

Blade thickness: 1 mm > 2 mm > 3 mm.

Rake angle: 40° > 50° > 30° > 90°.

Blades with a thickness of 1 mm exhibited greater insertion compliance than the others, whereas a rake angle of 40° offered the optimal balance between cutting resistance and effective insertion with high structural compliance. Extreme rake angles, especially 90° are more mechanically inefficient than others because they require excessive force.

CONCLUSION

This study evaluated the significance of blade thickness (1-3 mm) and rake angle (30°-90°) on the insertion depth and piercing force on the Jigat tree. The best performance was obtained with a 1 mm blade at a 40° rake angle, as it required the least piercing force while ensuring effective insertion

and the highest structural compliance. However, owing to repeated impact loads, the 1 mm blade did not possess adequate durability; therefore, a 2 mm blade was recommended for debarking.

The piercing force increased with thicker blades and higher rake angles as the blade thickness increased and the insertion compliance was decreased. A rake angle of 40° offered the optimal compromise between cutting resistance and insertion, in contrast to lower (30°) and very high angles (90°). The average moisture content of the bark was assessed using the oven-dry method by drying samples of known weight at 103°C for 24 h, yielding a moisture content of 58.4%. Bark hardness was measured using a texture analyzer and recorded as 490 N at 50% compression with a penetration depth of 5 mm. These results indicated that this improved mechanical debarking designs lowered the effort required for piercing and reduced the energy use, which in turn increased the debarking process faster and more effective.

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Disclaimers

The views and conclusions expressed in this article are solely those of the authors and do not necessarily represent the views of their affiliated institutions. The authors are responsible for the accuracy and completeness of the information provided, but do not accept any liability for any direct or indirect losses resulting from the use of this content.

Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication.

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