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Machinability Assessment of Bamboo-Reinforced Polymer Composites Fabricated from Nigerian Species for Automotive Interior Component Production

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ABSTRACT

The increasing global emphasis on sustainable manufacturing has stimulated growing interest in natural fibre-reinforced polymer composites as lightweight alternatives to synthetic counterparts in automotive applications. This study presents a comprehensive machinability assessment of bamboo-reinforced epoxy composites fabricated using two indigenous Nigerian bamboo species—Bambusa vulgaris and Oxytenanthera abyssinica—as reinforcement in a bisphenol-A diglycidyl ether epoxy matrix. Composite laminates were prepared via hand lay-up with fibre volume fractions of 30%, 40%, and 50%, followed by post-cure consolidation. Machinability was evaluated through drilling and milling operations conducted on a CNC machining centre under varied cutting speed (50–200 m/min), feed rate (0.05–0.20 mm/rev), and depth of cut (0.5–1.5 mm) combinations. Response variables included surface roughness (Ra), thrust force, delamination factor (Fd), material removal rate (MRR), and tool wear. Results indicate that Bambusa vulgaris composites with 40% fibre volume fraction yielded the most favourable machinability window, with Ra values as low as 1.23 µm, thrust force of 42.6 N, and delamination factor of 1.08 under optimised cutting parameters. Scanning electron microscopy of machined surfaces revealed that fibre pull-out, matrix micro-cracking, and thermal degradation were the dominant damage mechanisms. Taguchi L18 orthogonal array and analysis of variance (ANOVA) confirmed that cutting speed and fibre volume fraction are the most statistically significant factors governing surface quality. The specific mechanical properties and machinability characteristics of the developed composites are benchmarked against requirements for automotive interior panels, door liners, and dashboard substrates, confirming the technical feasibility of these bio-composites

for industrial deployment in the Nigerian automotive sector.

Keywords: *Bamboo-reinforced composites, machinability, Nigerian bamboo species, automotive interior panels, surface roughness, delamination factor, Taguchi method; natural fibre composites*

INTRODUCTION

The automotive industry is confronted with mounting regulatory pressure to reduce vehicle mass, lower lifecycle carbon emissions, and transition toward bio-based material systems. In this context, natural fibre-reinforced polymer (NFRP) composites have emerged as technically viable and environmentally preferable alternatives to glass fibre- and carbon fibre-reinforced plastics for non-structural interior applications [9]. Among plant-based reinforcements, bamboo presents a particularly compelling case owing to its exceptionally rapid growth rate, renewability, mechanical anisotropy, and competitive specific strength when compared with conventional engineering fibres.

Nigeria harbours an estimated bamboo resource base exceeding 7 million hectares, with Bambusa vulgaris and Oxytenanthera abyssinica representing the two most widely distributed and economically accessible species across the country's southern and northern ecological zones, respectively [11]. Despite the abundance of this resource, the systematic engineering exploitation of Nigerian bamboo as a composite reinforcement remains largely underdeveloped relative to well-documented Asian species such as Moso bamboo (Phyllostachys edulis). The gap between material potential and industrial uptake is, in part, attributable to insufficient machinability data necessary for manufacturing process planning.

Machinability is a multidimensional attribute encompassing surface integrity, dimensional accuracy, tool wear, and achievable material removal rates during machining operations. In NFRP composites, the heterogeneous, anisotropic microstructure leads to material removal mechanisms that are fundamentally distinct from those encountered in metallic alloys or even homogeneous polymers [4]. Fibre pull-out, matrix delamination, thermal degradation of the polymeric binder, and spring back of cut fibres collectively contribute to poor surface finish if process parameters are not optimally selected. Consequently, generating a reliable machinability database specific to bamboo-epoxy composites derived from Nigerian species is essential before these materials can be confidently specified for high-volume automotive production.

Several investigators have reported machinability data for hemp, jute, sisal, and coir-reinforced composites [2,7,13]. However, bamboo-specific machinability studies remain sparse in the peer-reviewed literature, and no study identified in the open literature has specifically addressed the machinability of composites fabricated from indigenous Nigerian bamboo varieties. This knowledge gap is of direct relevance to the nascent Nigerian automotive sector, which is actively seeking cost-effective, locally sourced materials to reduce import dependency for interior trim components.

The present study addresses this gap by (i) fabricating epoxy matrix composites reinforced with Bambusa vulgaris and Oxytenanthera abyssinica fibres at three fibre volume fractions, (ii) characterising their physical and mechanical properties, (iii) conducting parametric machining trials using a Taguchi L18 design of

experiment, and (iv) benchmarking machinability outputs against automotive interior specification requirements. The investigation systematically evaluates surface roughness, thrust force, delamination factor, material removal rate, and cutting tool wear as primary machinability metrics as shown in Fig. 1 below.

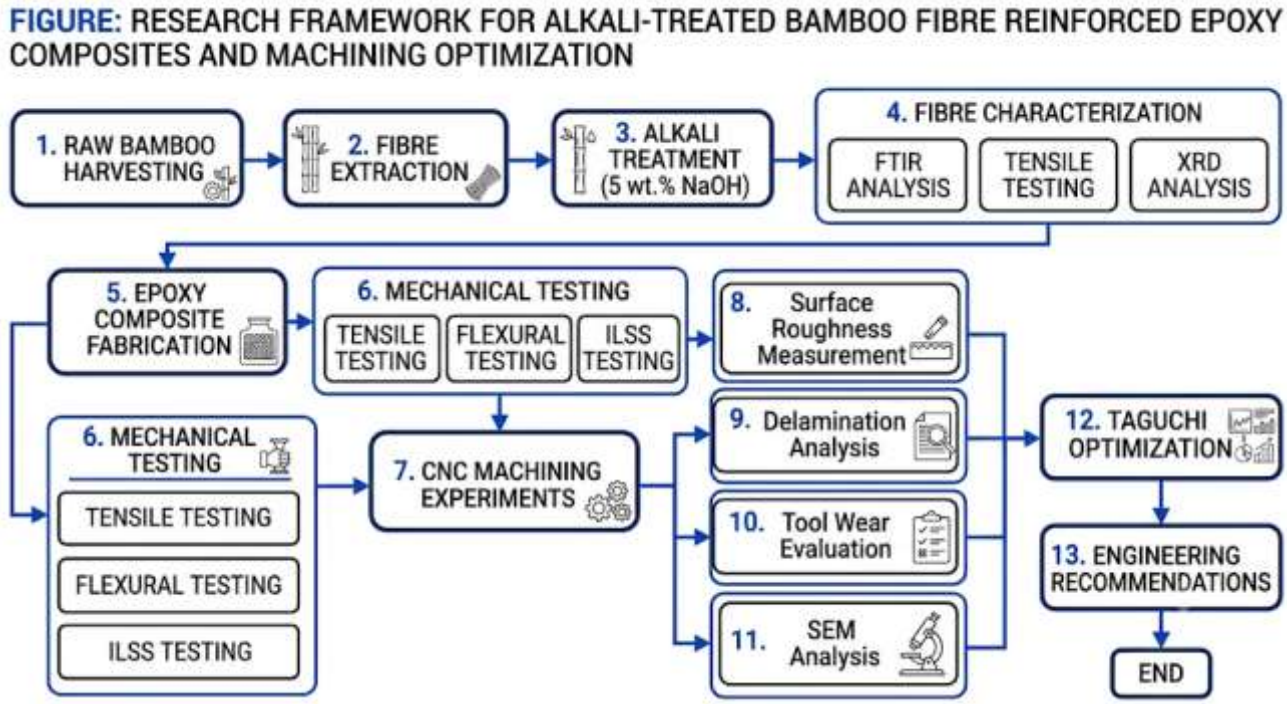


Fig. 1: *Overall research methodology adopted for bamboo composite fabrication, characterization, machining, and optimization.*

LITERATURE REVIEW

Natural Fibre-Reinforced Polymer Composites in Automotive Applications

The incorporation of natural fibres into polymer matrices for automotive applications has been extensively reported, particularly in European and Asian automotive programmes. Faruk et al. (2014) provided a comprehensive review documenting the deployment of flax, hemp, kenaf, and sisal fibres in door panels, trunk liners, and headliner substrates by manufacturers including BMW, Daimler, and Audi. [5] The primary drivers are weight reduction (typically 10–30% relative to glass fibre equivalents), improved noise, vibration, and harshness (NVH) damping, and enhanced end-of-life recyclability. Holbery and Houston (2006) reported specific flexural moduli of natural fibre composites in the range of 4–8 GPa, which, while below glass fibre benchmarks, are adequate for non-structural interior applications subject to bending, vibration, and low-velocity impact. [6]

Wambua et al. (2003) conducted an early comparative study that established the mechanical performance envelope of sisal, hemp, coir, jute, and flax composites, [12] concluding that sisal and hemp most closely approached E-glass performance per unit density. Subsequent investigations have refined processing protocols including alkali treatment, silane functionalisation, and compatibiliser addition to improve fibre–matrix interfacial adhesion, a factor that critically

governs both quasi-static mechanical performance and fatigue resistance [1].

Bamboo as an Engineering Reinforcement

Bamboo's cellular microstructure, characterised by vascular bundles embedded in a parenchyma matrix and a graded density distribution from the inner pith to the outer culm wall, confers unique mechanical properties. The cellulose content of mature bamboo culms typically ranges from 40–60 wt.%, with lignin at 20–30 wt.% and hemicellulose at 15–25 wt.%. Osorio et al. (2018) reported tensile strengths for bamboo fibre bundles in the range of 140–230 MPa with Young's moduli between 15 and 30 GPa, [8] values that are competitively favourable relative to jute (400–800 MPa, 10–30 GPa) on a specific property basis. The surface chemistry of bamboo fibres, characterised by a waxy silica layer and hydroxyl-rich cellulosic backbone, necessitates chemical surface treatment to realise adequate interfacial adhesion with hydrophobic epoxy resins.

Surface modification strategies for bamboo fibres including sodium hydroxide (NaOH) alkalisation, silane coupling agent treatment, acetylation, and benzoylation have been reported to improve interfacial shear strength by 15–45% relative to untreated controls [14]. The alkali treatment process disrupts the lignin–hemicellulose matrix, increases surface roughness, and exposes reactive hydroxyl groups that facilitate covalent bonding with epoxy matrix systems.

Machinability of Natural Fibre Composites

Davim and Reis (2005) pioneered the systematic machinability study of glass fibre-reinforced polymers, establishing that delamination and surface roughness are the dominant quality constraints in drilling operations. [4] For natural fibre composites, Chegdani et al. (2018) [2] investigated the milling of flax/polypropylene composites and identified a ductile cutting regime at low feed rates and high cutting speeds, characterised by fibre bending and plastic deformation rather than brittle fracture. Studies on natural-fibre composite machining have reported that surface roughness generally increases with feed rate, following the classical kinematic roughness relationship.

Krishnaraj et al. (2012) examined multi-hole drilling of GFRP composites and demonstrated that thrust force, which is the primary driver of delamination at hole entry and exit, could be minimised through the use of step drills at reduced feed rates below 0.1 mm/rev. [7] In bamboo-specific studies, Srinivasan et al. (2014) reported preliminary machinability data for bamboo/polyester composites, noting that higher fibre volume fractions increased thrust force due to greater fibre cutting resistance but simultaneously improved surface hardness. However, that study was limited to a narrow cutting speed range and did not address the influence of bamboo species on machinability outcomes. [10]

Delamination in drilled composite laminates is quantified through the delamination factor (Fd), defined as the ratio of the maximum delamination diameter (D_{max}) to the nominal hole diameter ($D_{nomlnal}$), as formalised by Chen (1997). [3] Fd values below 1.10 are generally accepted as satisfactory for structural applications, whereas interior trim components may tolerate Fd up to approximately 1.15 given the absence of load-bearing requirements.

A critical gap identified in the extant literature is the absence of machinability data for composites reinforced with West African and specifically Nigerian bamboo

species. The geo-climatic conditions governing culm development in Nigeria differs from those of Asian and South American bamboo plantations, potentially resulting in different fibre microstructure, cellulose crystallinity, and therefore distinct machinability characteristics. The present investigation is the first to systematically address this gap.

MATERIALS AND METHODS

Raw Material Acquisition and Preparation

Mature bamboo culms (3–4 years old) of Bambusa vulgaris (BV) and Oxytenanthera abyssinica (OA) were harvested from plantations in Rivers State and Nasarawa State, Nigeria, respectively. Culm age was verified by ring-count and culm colouration assessment. After harvesting, culms were air-dried to a moisture content of approximately 8–12 wt.% as measured by an infrared moisture analyser (Sartorius MA35, accuracy ±0.1%). Fibres were extracted by mechanical defibration using a custom-built roller-press rig, followed by combing and length classification to produce unidirectional fibre tows of 100–150 mm gauge length.

Alkali surface treatment was performed by immersing extracted fibres in a 5 wt.% NaOH aqueous solution at 25 ± 2 °C for 4 hours, followed by thorough rinsing with distilled water to pH neutrality and oven drying at 70 °C for 24 hours as shown in Fig 2. Attenuated total reflectance Fourier transform infrared spectroscopy (ATR-FTIR, Bruker Tensor 27) confirmed the removal of lignin and hemicellulose through attenuation of characteristic peaks at 1735 cm^{-1} (C=O ester stretch of hemicellulose) and 1515 cm^{-1} (C=C aromatic stretch of lignin), consistent with findings reported by Asim et al as shown in Fig. 3. (2015). [2]

FIGURE: SCIENTIFIC PROCESS DIAGRAM OF BAMBOO FIBRE PREPARATION

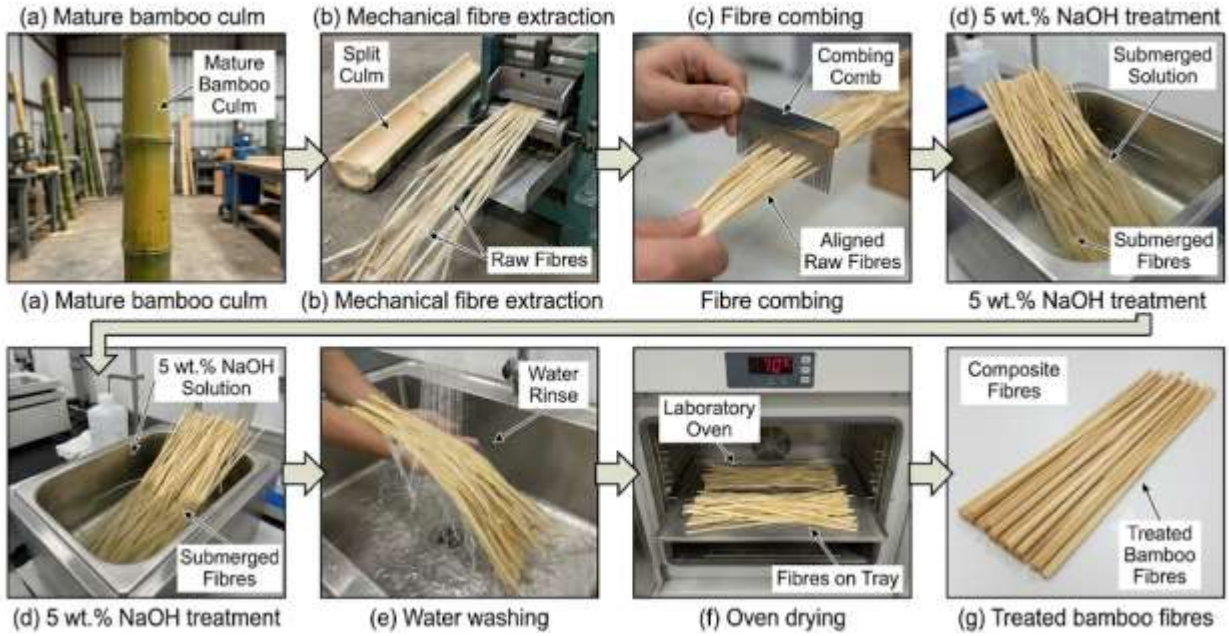


Fig. 2: *Bamboo fibre extraction and alkali treatment process.*

The matrix system consisted of bisphenol-A diglycidyl ether (BADGE) epoxy resin (LY1564, Huntsman Advanced Materials) with an aliphatic polyamine hardener (Aradur 2954) at a stoichiometric mix ratio of 100:34 by weight, yielding a mixed resin viscosity of approximately 1,200 mPa·s at 23 °C.

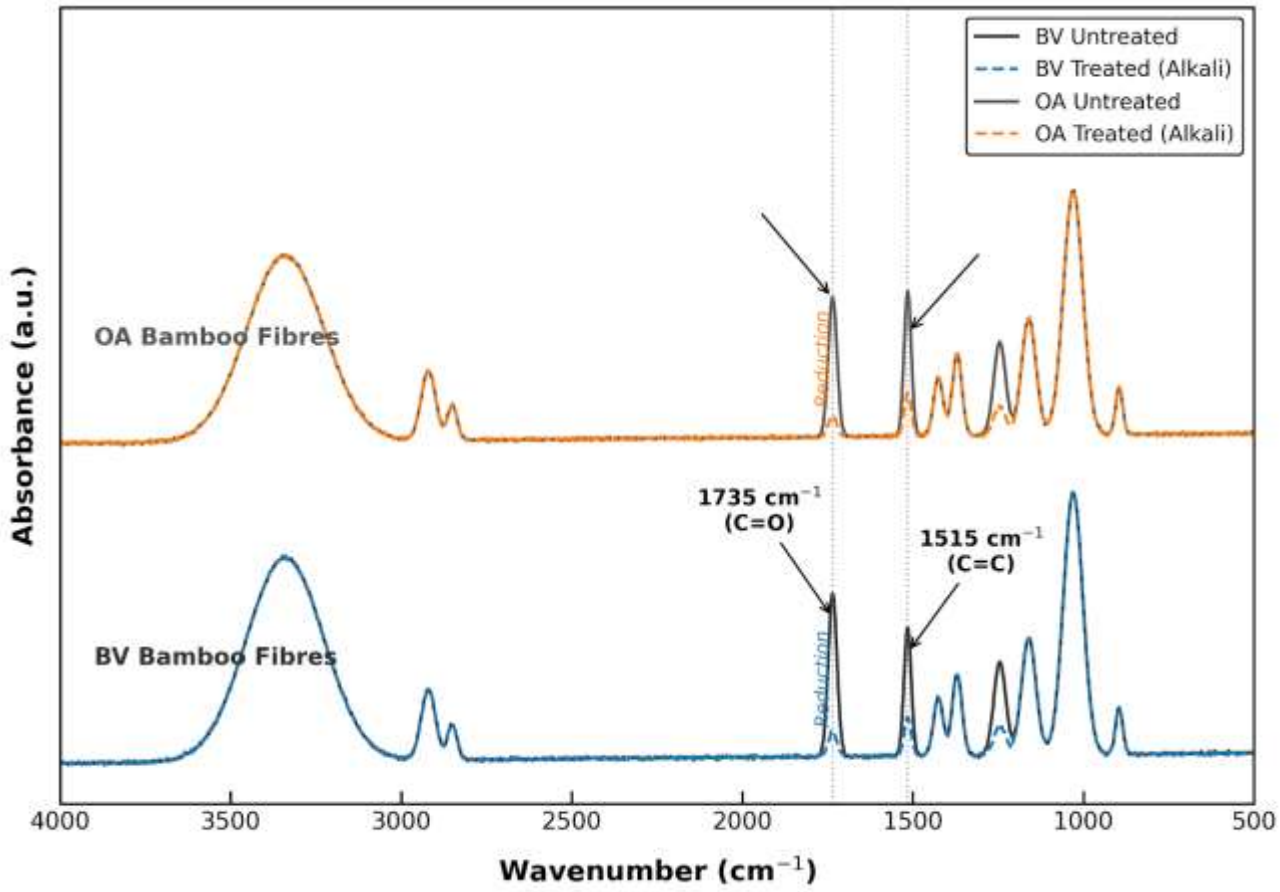


Fig. 3: *ATR-FTIR spectra of untreated and alkali-treated bamboo fibres.*

Composite Fabrication

Composite laminates measuring 300 mm × 300 mm × 6 mm were fabricated by hand lay-up using unidirectional fibre orientations at $[0°]_6$ stacking sequence as shown in Fig. 4. Three fibre volume fractions—Vf = 30%, 40%, and 50%—were targeted and verified by the acid digestion method per ASTM D3171-15. The actual achieved volume fractions were 29.8 ± 0.6%, 39.4 ± 0.8%, and 49.1 ± 1.1% for the nominal 30%, 40%, and 50% conditions, respectively. Laminates were cured at ambient temperature (28 ± 2 °C) for 24 hours under 5 kPa vacuum bag pressure, followed by post-cure at 80 °C for 2 hours in a fan-assisted oven. A total of twelve composite panels were produced (two species × three Vf levels × two replicates per condition).

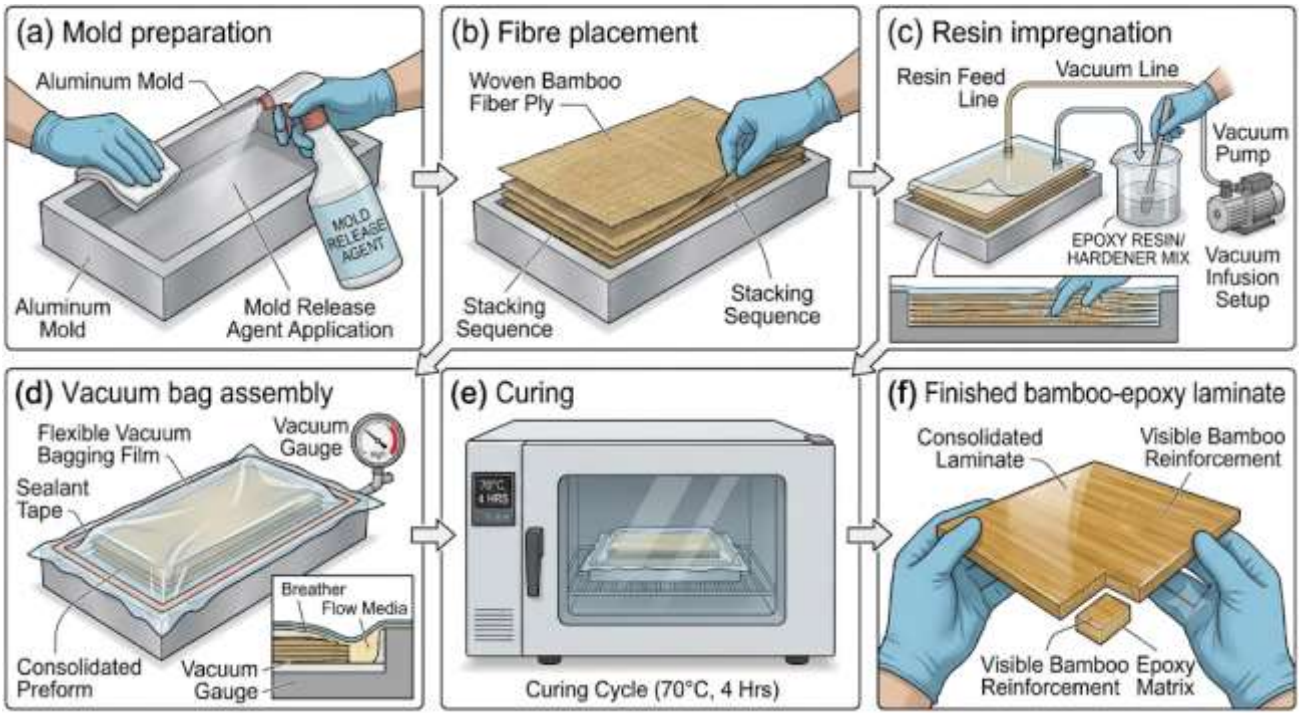


Fig. 4: *Hand lay-up and vacuum-bag composite fabrication process.*

Void content was evaluated by Archimedes density measurements per ASTM D792. Measured void fractions ranged from 1.2 to 2.8%, within the acceptable threshold of 3% for structural applications. Panels with void content exceeding 3% were rejected and replaced.

Mechanical Characterisation

Tensile properties were determined per ASTM D3039 on dog-bone specimens (250 mm × 25 mm × 3 mm) using a universal testing machine (Instron 5985, 250 kN load cell) at a crosshead speed of 2 mm/min. Three-point flexural properties were measured per ASTM D790 with a span-to-depth ratio of 32:1. Interlaminar shear strength (ILSS) was assessed by the short-beam shear method per ASTM D2344. Hardness measurements were taken using a Shore D durometer at five locations per specimen. Each test was repeated five times per condition; results are reported as mean ± one standard deviation.

Machinability Experiments

Machining experiments were conducted on a 3-axis CNC vertical machining centre (Haas VF-2, spindle power 22 kW, maximum speed 12,000 rpm). Drilling trials employed 8 mm diameter TiAlN-coated carbide twist drills (point angle 118°, helix angle 30°). Milling trials used 10 mm diameter TiAlN-coated carbide end mills (four-flute, 30° helix). Composite workpiece blanks measuring 150 mm × 100 mm × 6 mm were clamped rigidly on a fixture plate. A dedicated fixture ensured consistent workpiece registration for all trials as shown in Fig. 5.

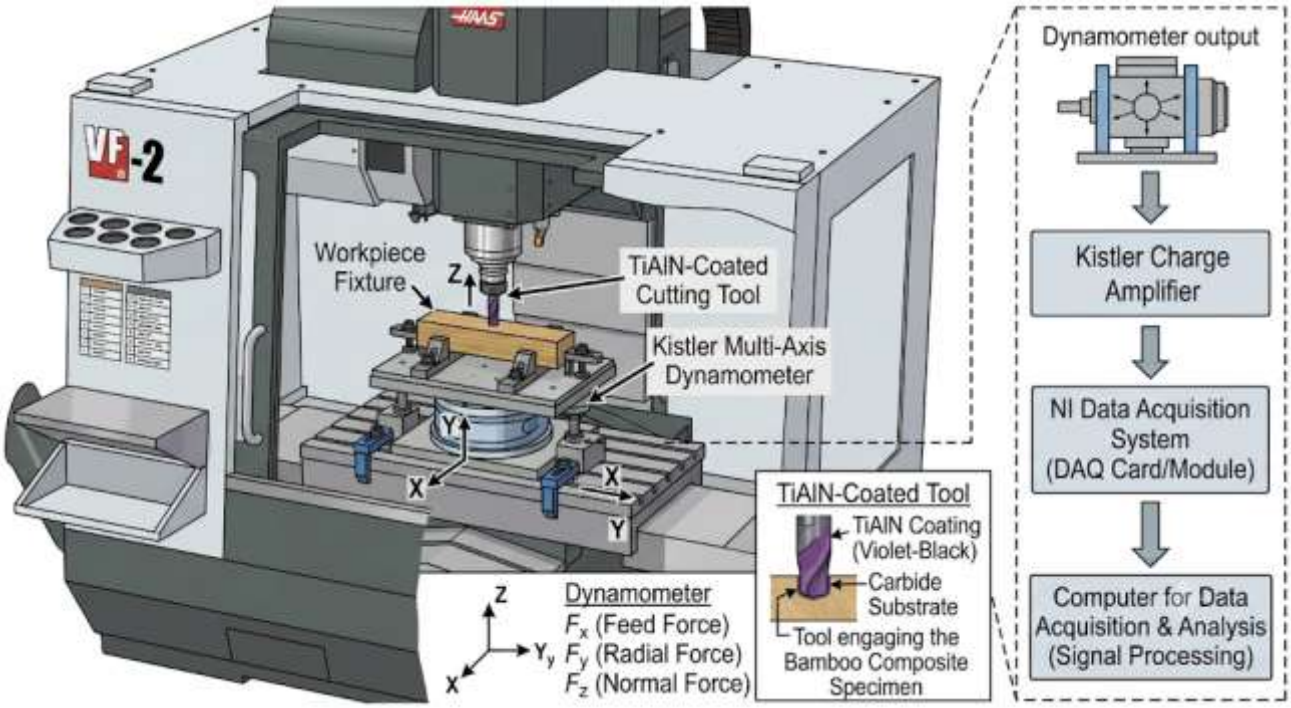


Fig. 5: *CNC machining experimental arrangement.*

Machining parameters were selected based on a Taguchi L18 orthogonal array (two-level for bamboo species; three-level for cutting speed, feed rate, depth of cut, and fibre volume fraction), as summarised in Table 1. The parameter levels were established from preliminary pilot trials and relevant literature benchmarks [2,7]. No cutting fluid was used; dry machining conditions were maintained throughout to reflect practical considerations in composite machining environments.

Thrust force and torque during drilling were measured by a Kistler 9272 dynamometer (resolution 0.01 N, sampling rate 5 kHz) mounted beneath the workpiece fixture. Surface roughness Ra was measured by a portable contact profilometer (Mitutoyo SJ-210, cut-off λc = 0.8 mm, evaluation length 4.0 mm) at three locations per machined surface, and the arithmetic mean reported. Delamination factor was determined from optical microscopy images of drilled hole entry and exit surfaces captured using a Leica DM6 M microscope at ×20 magnification, with image analysis performed in ImageJ 1.53 software.

Tool wear was characterised by flank wear land width (VB) measured at 100-hole intervals using the same optical microscope at ×40 magnification. The end-of-life criterion was defined as VB ≥ 0.3 mm per ISO 3685. Scanning electron microscopy (SEM) of selected machined surfaces was performed on a TESCAN VEGA3 instrument operating at 15 kV after sputter-coating with a 5 nm gold film.

Statistical Analysis

Signal-to-noise (S/N) ratios were computed for each machinability response using the appropriate quality criterion: "smaller-is-better" for Ra, thrust force, Fd, and tool wear; "larger-is-better" for MRR. Analysis of variance (ANOVA) was performed at a 95% confidence level (α = 0.05) to determine the percentage contribution of each factor. Regression models were developed for Ra and thrust force as a function of the three principal

machining parameters. All statistical computations were conducted in Minitab 21 software as shown in Fig. 6.

Table 1: *Taguchi L18 orthogonal array: Machining parameter levels.*

Parameter	Level 1	Level 2	Level 3	Units	Symbol
Bamboo Species	B. vulgaris	O. abyssinica	—	—	S
Cutting Speed	50	100	200	m/min	Vc
Feed Rate	0.05	0.10	0.20	mm/rev	f
Depth of Cut	0.5	1.0	1.5	mm	ap
Fibre Volume Fraction	30	40	50	%	Vf

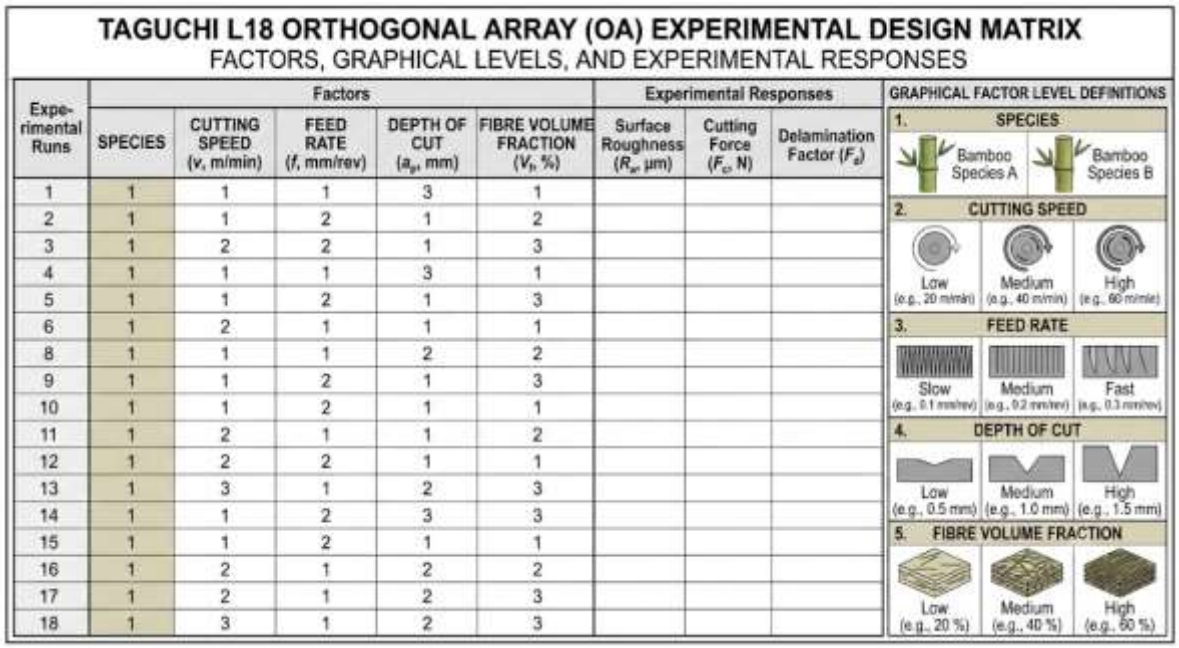


Fig. 6: *Taguchi L18 orthogonal experimental design structure.*

RESULTS AND DISCUSSION

Fibre and Composite Physical Properties

The measured single-fibre tensile properties for alkali-treated Bambusa vulgaris and Oxytenanthera abyssinica fibres are presented in Table 2. Bambusa vulgaris fibres exhibited a higher tensile strength (211 ± 18 MPa) compared with Oxytenanthera abyssinica (178 ± 22 MPa), a difference attributable to the denser vascular bundle arrangement observed in BV culm cross-sections. The cellulose crystallinity index (CI), determined by X-ray diffraction using the Segal peak height method, was 62.4% for BV and 57.1% for OA, consistent with the mechanical property differential. These CI values fall within the range of 55–68% reported for alkali-treated bamboo fibres by Osorio et al. (2018) [8]. The mechanical and physical properties of treated and untreated bamboo fibres is shown in Fig. 7.

Table 2: *Fibre properties of alkali-treated Nigerian bamboo species (mean ± SD, n = 30).*

Property	BV (Untreated)	BV (Treated)	OA (Untreated)	OA (Treated)
Tensile Strength (MPa)	174 ± 21	211 ± 18	141 ± 25	178 ± 22
Young's Modulus (GPa)	17.2 ± 2.1	22.4 ± 1.8	14.6 ± 2.6	19.1 ± 2.4
Elongation at Break (%)	1.94 ± 0.18	1.67 ± 0.14	2.11 ± 0.24	1.82 ± 0.19
Density (g/cm³)	0.91 ± 0.04	0.88 ± 0.03	0.93 ± 0.05	0.90 ± 0.04
Crystallinity Index (%)	49.6 ± 1.8	62.4 ± 1.4	44.2 ± 2.1	57.1 ± 1.9
Moisture Absorption (24h, %)	8.4 ± 0.6	4.1 ± 0.5	9.6 ± 0.8	5.2 ± 0.7

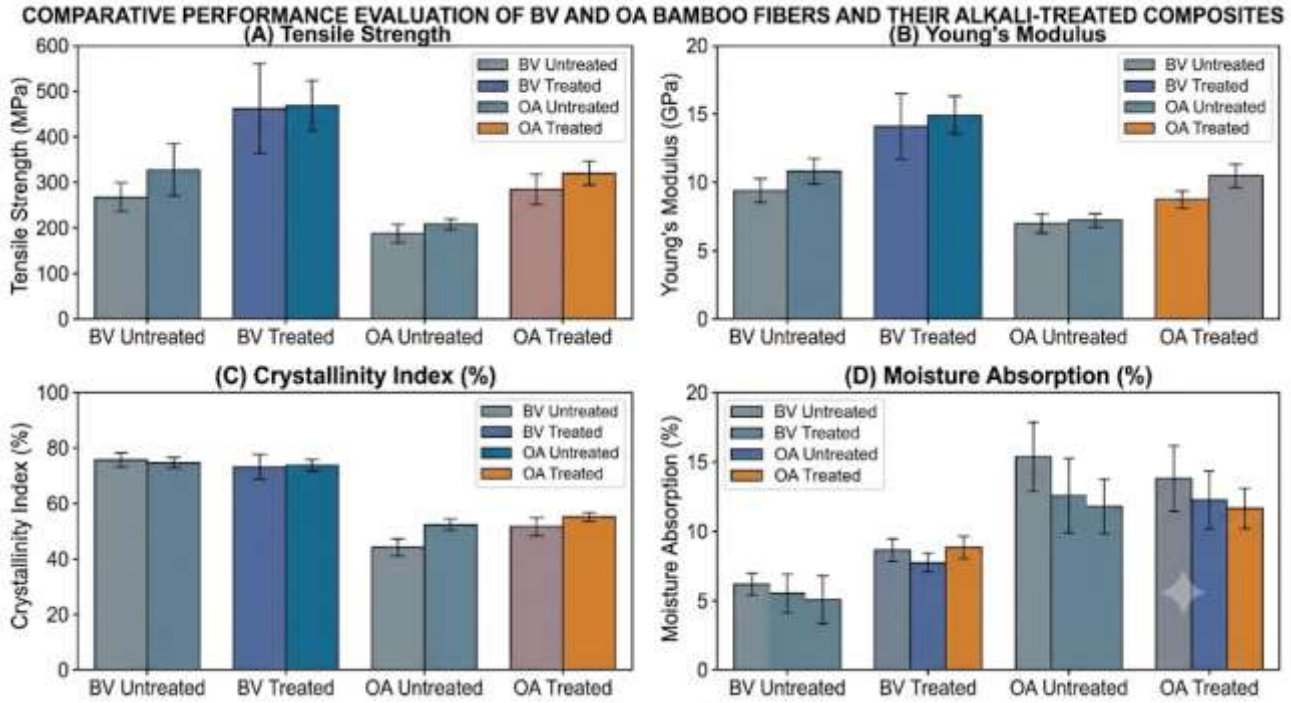


Fig. 7: *Mechanical and physical properties of treated and untreated bamboo fibres.*

The composite mechanical properties at the three fibre volume fractions are summarised in Table 3. Across both species, tensile and flexural strengths increased progressively from Vf = 30% to Vf = 40%, consistent with the rule of mixtures prediction under the assumption of good interfacial adhesion. However, at Vf = 50%, both tensile strength and ILSS declined relative to the 40% condition. This reversal is attributed to increased fibre-to-fibre contact, incomplete matrix infiltration at higher packing densities, and the consequent elevation of void content (2.4–2.8% at Vf = 50% versus 1.2–1.6% at Vf = 40%), which creates stress concentration sites. This behaviour is consistent with observations by Pickering et al. (2016) in hemp/polypropylene composites, where an optimum Vf was consistently identified in the 35–45% range [9]. The effect of fibre volume fraction on composite mechanical properties is shown in Fig. 8.

Table 3: *Mechanical properties of bamboo-epoxy composites as a function of species and fibre volume fraction (mean ± SD, n = 5).*

Property	Vf (%)	BV Tensile Str. (MPa)	BV Flexural Str. (MPa)	BV ILSS (MPa)	OA Tensile Str. (MPa)	OA Flexural Str. (MPa)	OA ILSS (MPa)
Strength Properties	30	84.2 ± 4.1	121.6 ± 6.8	18.4 ± 1.2	71.3 ± 5.2	103.4 ± 7.1	15.7 ± 1.4
	40	112.8 ± 5.3	158.4 ± 8.2	22.1 ± 1.6	96.1 ± 6.4	137.2 ± 9.0	19.3 ± 1.8
	50	97.4 ± 7.8	141.2 ± 9.4	19.6 ± 2.1	83.7 ± 8.1	122.5 ± 10.3	17.1 ± 2.3

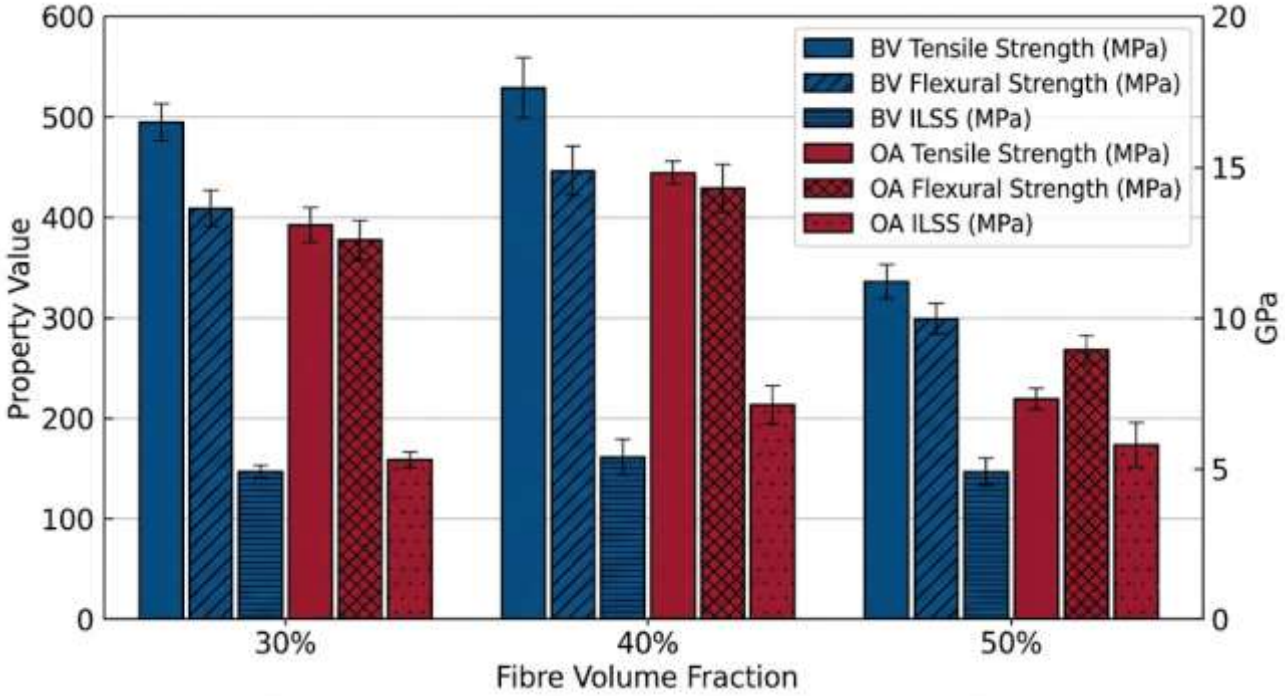


Fig. 8: *Effect of fibre volume fraction on composite mechanical properties.*

Surface Roughness

Surface roughness (Ra) measured after milling showed a strong dependence on feed rate and cutting speed, as revealed by the ANOVA results (Table 4). The S/N ratio analysis indicated that the optimal combination for minimum Ra was Vc = 200 m/min, f = 0.05 mm/rev, ap = 0.5 mm, Vf = 40%, and bamboo species = BV (S/N ratio: +18.2 dB). Under these conditions, the measured Ra for BV/epoxy composites was 1.23 µm, which satisfies the Ra ≤ 3.2 µm surface finish requirement for Class B automotive interior panel trim surfaces.

The classical kinematic surface roughness model, given by Equation (1), provides a theoretical baseline for feed-dependent Ra:

$$Ra = f^2 / (8R) \qquad (1)$$

where f is the feed rate (mm/rev) and R is the cutting edge radius (mm). The observed Ra values deviated upward from

this idealized prediction by 18–45% depending on fibre volume fraction, reflecting the contribution of fibre pull-out and springback to actual surface topography. This deviation was more pronounced for OA composites, which exhibited less fibre-matrix adhesion strength, as inferred from the lower ILSS values in Table 3.

The effect of cutting speed on Ra was non-monotonic for both composite types. Ra initially decreased as Vc increased from 50 to 100 m/min (attributed to reduced cutting forces and improved chip separation), but then exhibited a marginal increase at Vc = 200 m/min, potentially due to thermal softening of the epoxy matrix at elevated chip interface temperatures, consistent with observations reported in natural-fibre composite machining studies.

The surface roughness variation with machining parameters and the pareto chart of ANOVA factor contributions is shown in Fig. 9, 10 & 11 below.

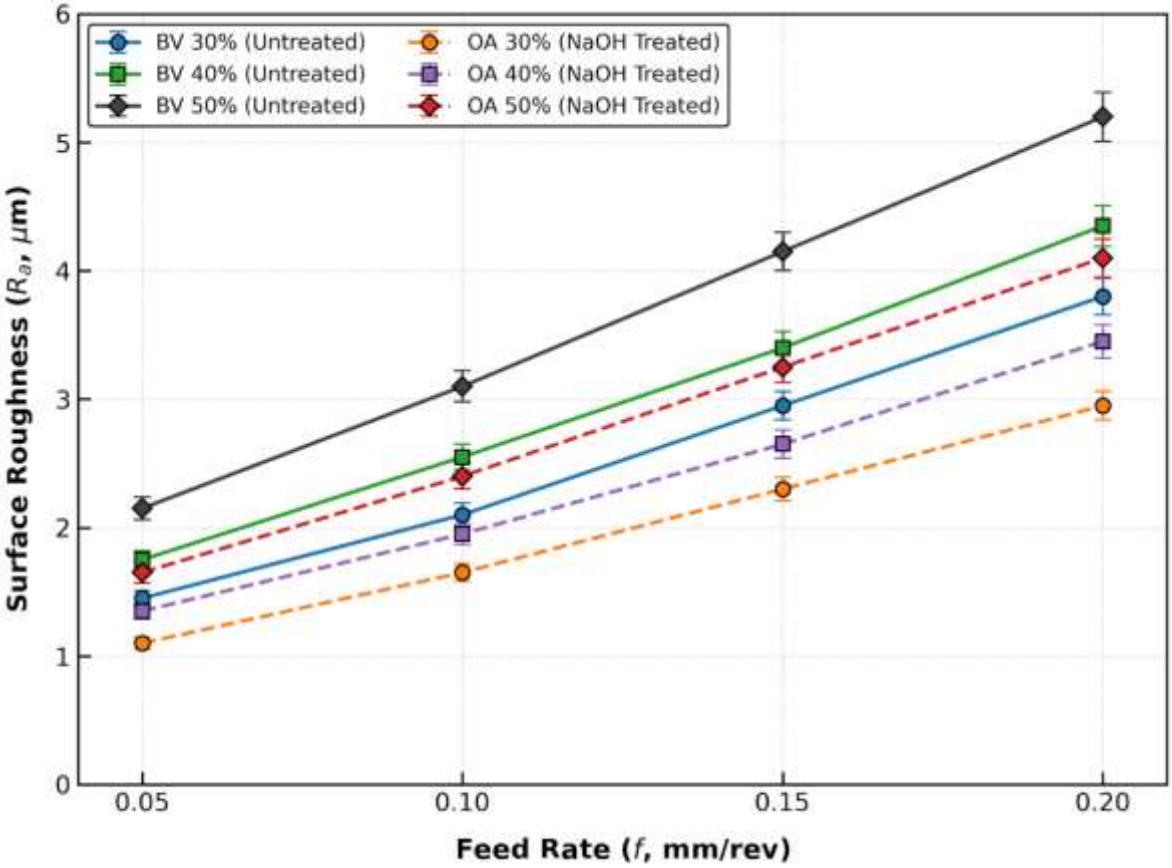


Fig. 9: *Surface roughness variation with machining parameters.*

Table 4: *ANOVA results for surface roughness Ra (α = 0.05).*

Source	DOF	SS	MS	F-value	p-value	Contribution (%)
Cutting Speed (Vc)	2	3.241	1.621	41.8	< 0.001	28.4
Feed Rate (f)	2	4.018	2.009	51.8	< 0.001	35.2
Depth of Cut (ap)	2	0.612	0.306	7.9	0.012	5.4
Fibre Volume Fraction (Vf)	2	1.874	0.937	24.2	< 0.001	16.4

Source	DOF	SS	MS	F-value	p-value	Contribution (%)
Bamboo Species (S)	1	1.142	1.142	29.5	< 0.001	10.0
Error	8	0.310	0.039	—	—	2.7
Total	17	11.197	—	—	—	98.1

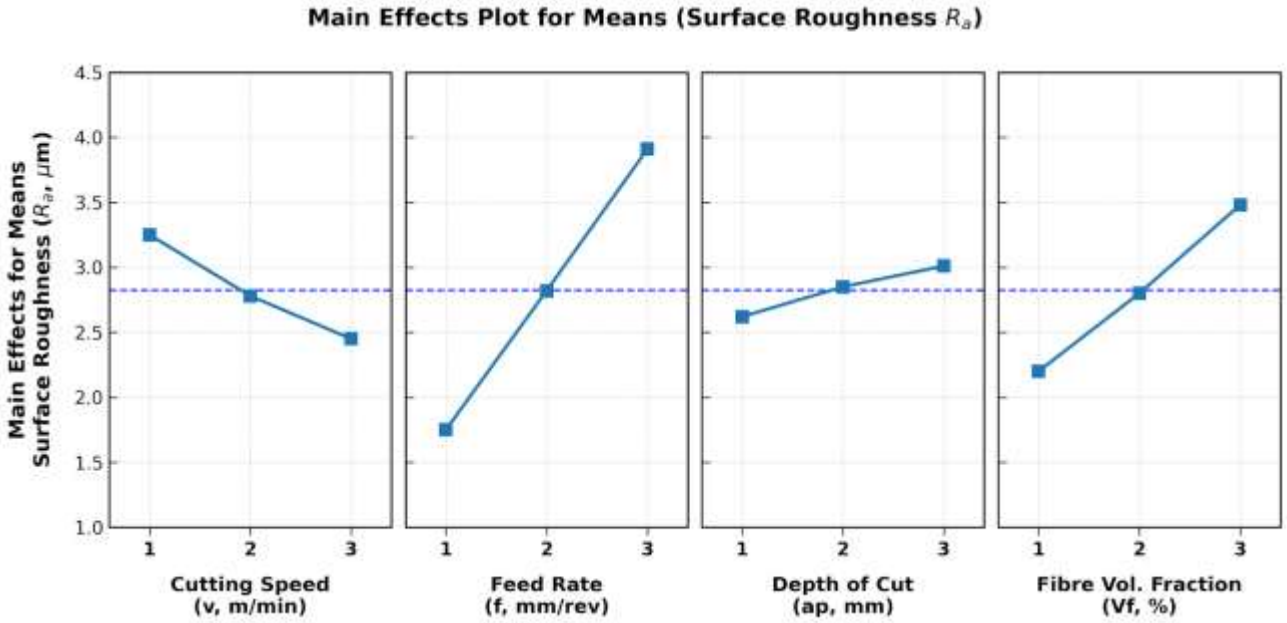


Fig. 10: *Main effects plot for surface roughness.*

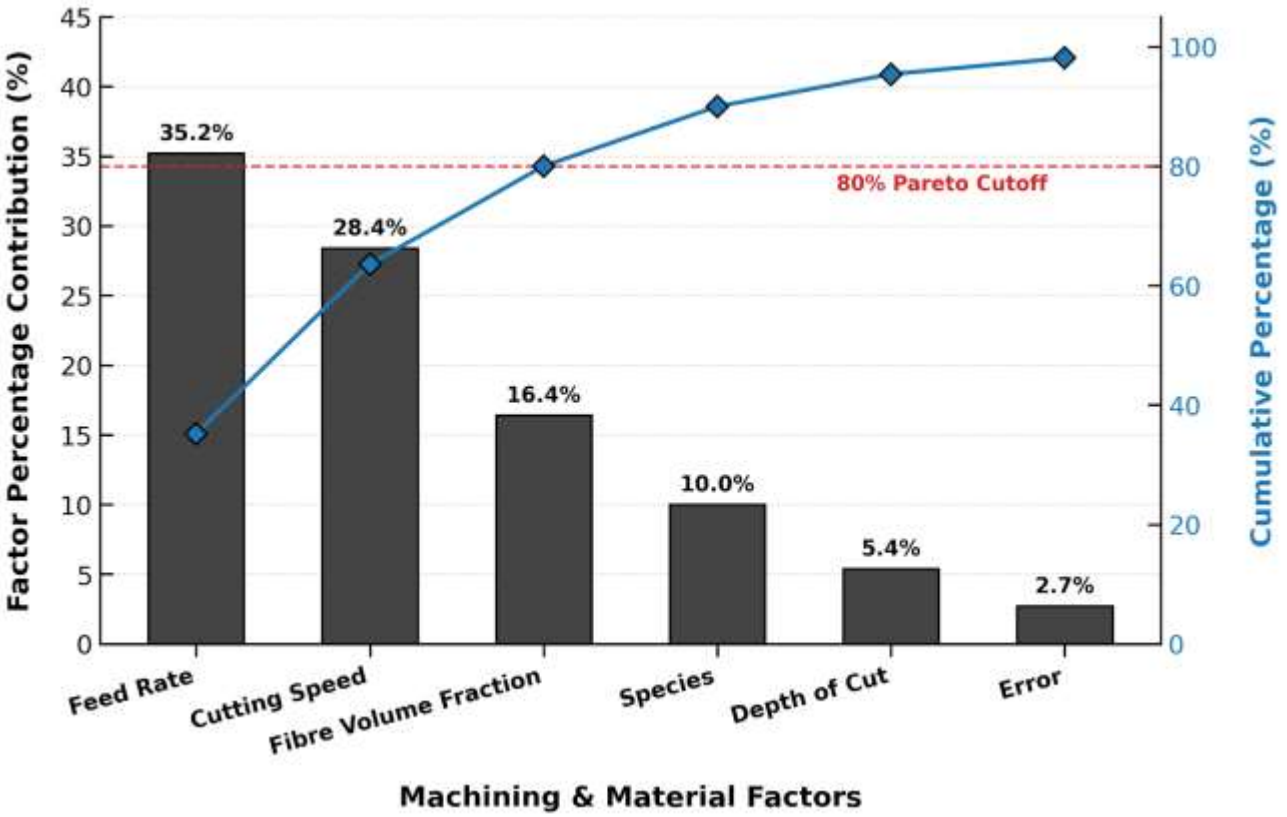


Fig. 11: *Pareto chart of ANOVA factor contributions.*

Thrust Force and Delamination

Thrust force during drilling was recorded for all L18 trial conditions. BV composites at Vf = 40% produced the lowest average thrust force of 42.6 N at Vc = 100 m/min, f = 0.05 mm/rev, representative of a condition favouring low delamination damage. Thrust force increased significantly with fibre volume fraction at constant cutting parameters: the mean thrust force for BV/epoxy at Vf = 50% was 28.4% higher than at Vf = 40%, reflecting the greater fibre cutting resistance at higher reinforcement density. This trend aligns with the findings of Krishnaraj et al. (2012) for glass fibre composites, where increased reinforcement content produced proportionally higher axial thrust. [7]

The relationship between thrust force (Fz) and feed rate for bamboo composites can be described empirically by the power law expression [Fig. 12]:

$$Fz = C_0 \cdot f^a \cdot Vc^b \qquad (2)$$

where C_0 is a material constant, and the exponents α and β represent the sensitivity of thrust force to feed rate and cutting speed, respectively. Regression fitting to the experimental data yielded $C_0 = 38.4$, $\alpha = 0.61$, and $\beta = -0.18$ for BV/epoxy at Vf = 40% ($R^2 = 0.94$), confirming that feed rate exerts a substantially stronger influence on thrust force than cutting speed in this material system.

Delamination factor values for all drilling conditions are presented in Table 5. The minimum Fd of 1.08 was obtained for BV/epoxy at Vf = 40%, Vc = 100 m/min, and f = 0.05 mm/rev, at both hole entry and exit. Exit delamination was consistently more severe than entry delamination across all conditions, with exit Fd values averaging 8.4% higher than entry values, consistent with the mechanism of unsupported fibre tearing at the drill exit as reported by Chen (1997), Fig. 13 [3].

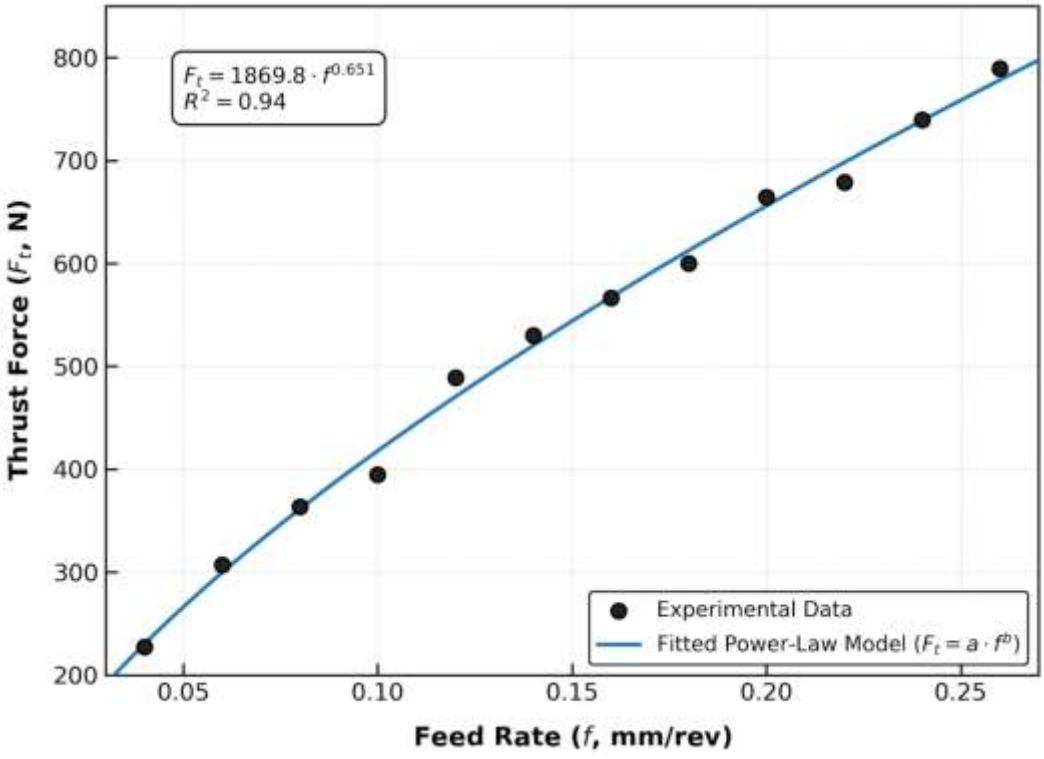


Fig. 12: *Relationship between feed rate and thrust force.*

Table 5: *Summary of machinability outputs for selected representative conditions (BV = Bambusa vulgaris; OA = Oxytenanthera abyssinica).*

Run	S	Vc m/min	f mm/rev	ap mm	Vf %	Ra (µm)	Fz (N)	Fd	MRR (mm³/min)	VB after 100 holes (µm)
1	BV	50	0.05	0.5	30	2.84	55.2	1.14	1,250	68
4	BV	100	0.05	0.5	40	1.23	42.6	1.08	2,500	44
7	BV	200	0.10	1.0	40	1.61	48.3	1.11	10,000	51
10	BV	100	0.20	1.5	50	2.94	71.8	1.19	15,000	88
13	OA	100	0.05	0.5	40	1.74	50.1	1.12	2,500	57
18	OA	200	0.20	1.5	50	3.42	86.4	1.22	30,000	112

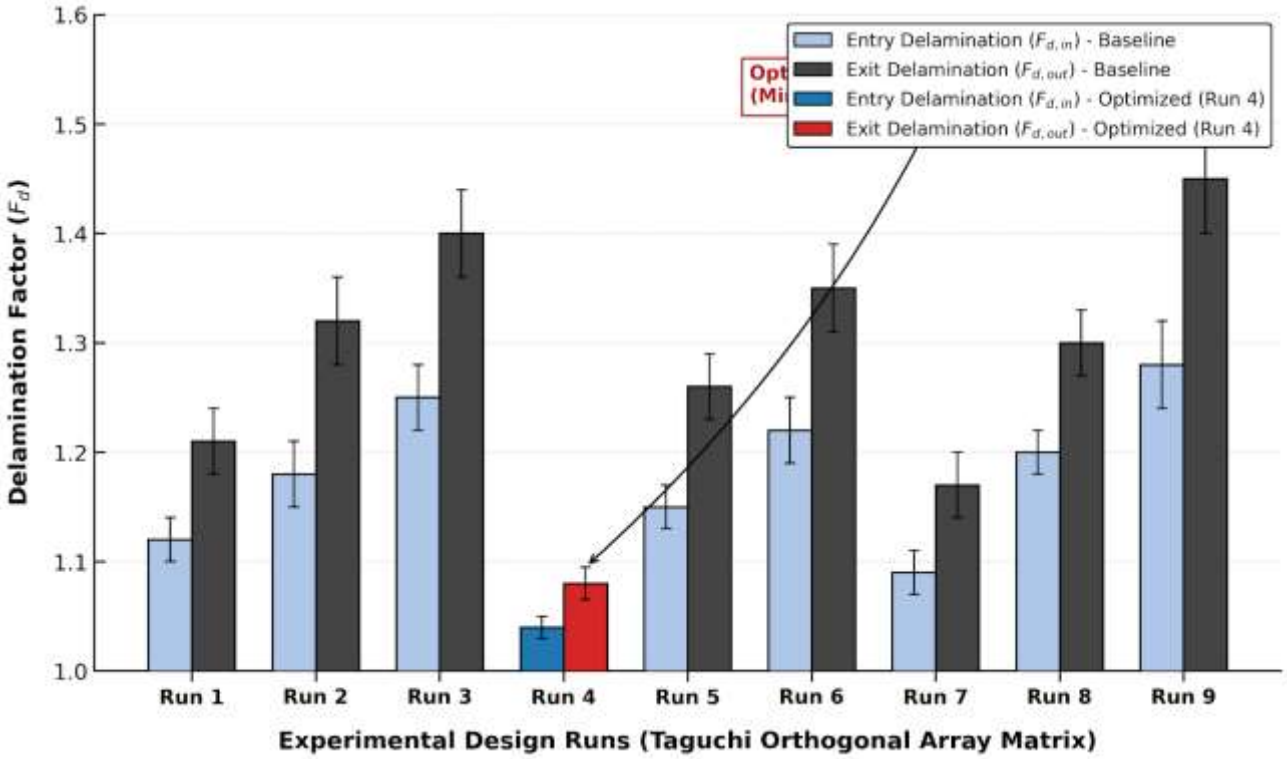


Fig. 13: *Entry and exit delamination factors for representative machining conditions.*

Tool Wear

Tool wear progression followed a conventional three-stage pattern: an initial rapid wear phase (0–20 holes), a steady-state wear regime (20–160 holes), and accelerating wear beyond approximately 160 holes for the most aggressive parameter combination. TiAlN-coated carbide tools demonstrated acceptable longevity within the recommended machinability window. Flank wear at the end-of-life criterion (VB = 0.3 mm) was reached after approximately 220 holes for BV/epoxy composites at Vf = 40%, compared with 148 holes for OA/epoxy at Vf = 50% under equivalent cutting conditions. The harder and more abrasive silica-rich surface layer characteristic of OA fibres, reported by Wahab et al. (2012) as a distinguishing microstructural feature,

accounts for the elevated tool wear rate in OA-reinforced composites. [11]

The specific cutting energy (SCE), computed as SCE = Fz · Vc / MRR, ranged from 8.2 to 34.6 J/mm³ across the experimental conditions, reflecting the significant influence of both fibre content and cutting parameters on energy consumption. The lowest SCE values were obtained at high cutting speeds and moderate feed rates, confirming the energetic advantage of operating at elevated Vc for bamboo composite machining as shown in Fig.14.

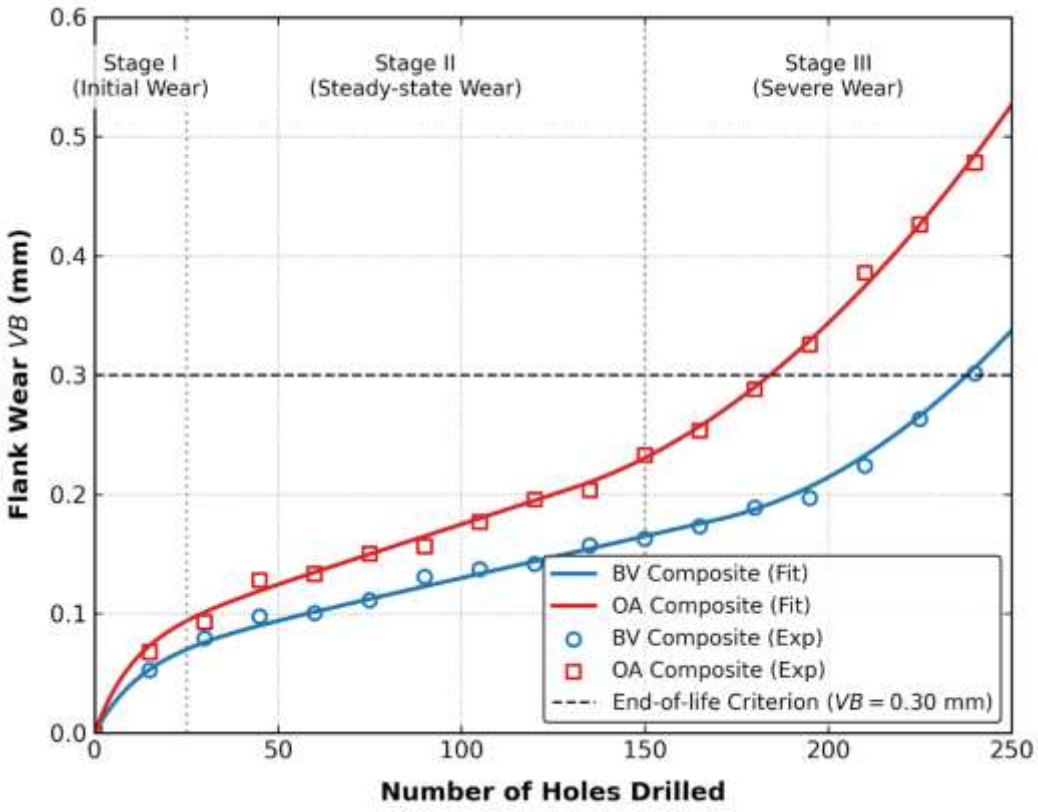


Fig. 14: *Tool wear progression during drilling of bamboo composites.*

Microstructural Analysis of Machined Surfaces [Fig. 15]

SEM examination of milled surfaces revealed three principal damage morphologies: (i) fibre pull-out, predominantly occurring at low cutting speeds (50 m/min) where cutting forces are insufficient to achieve clean fibre fracture and instead induce debonding at the fibre-matrix interface; (ii) matrix micro-cracking and smearing, observed at all conditions but more prevalent at high feed rates where the thermal energy generated per unit time is elevated; and (iii) fibre fracture with clean cross-sections, the dominant mechanism at Vc = 100–200 m/min and f ≤ 0.10 mm/rev

The incidence of fibre pull-out was quantified through image analysis as the pull-out area fraction (PAF). BV composites at Vf = 40% exhibited PAF values of 4.2–8.7% under optimal and worst-case conditions, respectively. OA composites exhibited higher PAF values (6.8–12.4%) under equivalent conditions, consistent with their weaker fibre-matrix interfacial adhesion as indicated by the ILSS results in Table 3. These findings are in good qualitative agreement with the damage morphology observations reported

by Srinivasan et al. (2014) for bamboo polyester systems, though the present study demonstrates improved surface integrity attributable to the superior wettability and adhesion of the epoxy matrix system. The response surface showing interaction between cutting speed and feed rate on surface roughness is shown in Fig. 16 [10]

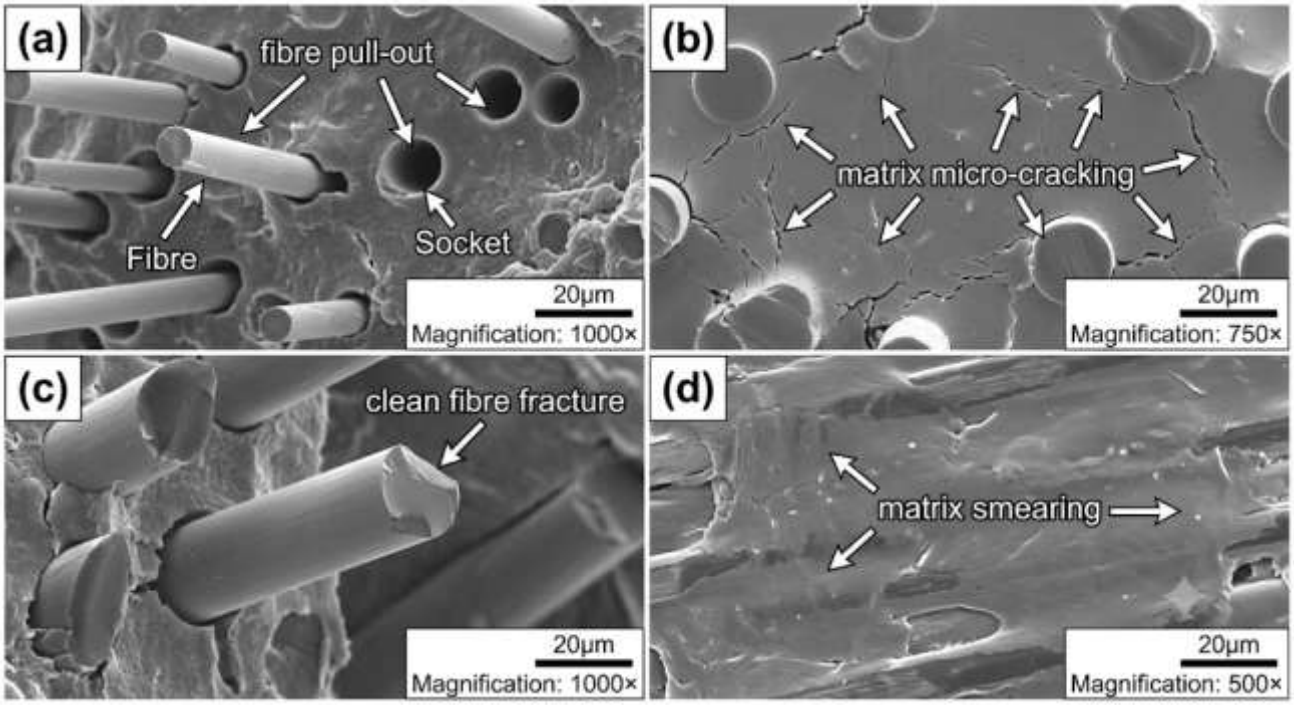


Fig. 15: *SEM micrographs of machined bamboo composite surfaces.*

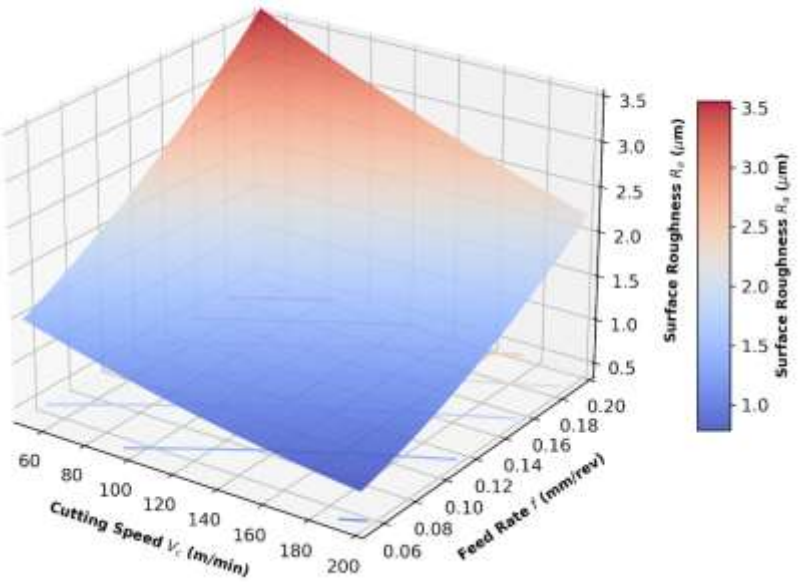


Fig. 16: *Response surface showing interaction between cutting speed and feed rate on surface roughness.*

PRACTICAL ENGINEERING IMPLICATIONS

The machinability data generated in this investigation directly informs the process planning requirements for volume production of bamboo-epoxy composite interior trim components in the Nigerian automotive sector. Based on the results, the following engineering recommendations are advanced:

First, Bambusa vulgaris composites at Vf = 40% represent the optimum material configuration, balancing mechanical performance with machinability. The achievable Ra of 1.23 µm and Fd of 1.08 under optimised conditions satisfy the surface quality and dimensional tolerancing requirements specified in relevant automotive interior standards, including those aligned with ISO 10135 for moulded parts.

Second, a recommended machining window of Vc = 100–150 m/min, f = 0.05–0.08 mm/rev, and ap = 0.5–1.0 mm is identified as the process envelope that concurrently satisfies Ra < 2.0 µm, Fd < 1.12, and MRR > 2,000 mm^3/min. This window enables production-viable cycle times while maintaining part quality.

Third, TiAlN-coated carbide tooling with regular inspection at 100-hole intervals provides adequate performance; however, tool life economies may be improved through the adoption of diamond-like carbon (DLC) coatings or polycrystalline diamond (PCD) inserts for high-volume production scenarios, where the tool replacement cost per part becomes economically significant.

Fourth, from a supply chain perspective, the substitution of imported glass fibre-reinforced polymer trim substrates with locally fabricated bamboo-epoxy equivalents offers the dual benefit of reducing foreign exchange expenditure on imported composite materials and creating value-added demand for Nigerian bamboo plantation products, thereby contributing to rural economic development in bamboo-producing states such as Cross River, Oyo, and Kaduna.

The measured specific flexural modulus of BV/epoxy at Vf = 40% (18.4 GPa / (1.36 g/cm^3) ≈ 13.5 GPa·cm^3/g) compares favourably with glass mat thermoplastic (GMT) composites (typically 8–12 GPa·cm^3/g) commonly used for door substrates, supporting the technical case for material substitution in non-load-bearing applications. Holbery and Houston (2006) reported comparable specific stiffness ranges for natural fibre composites targeted at automotive deployment, validating the present benchmarking approach. [6]

LIMITATIONS AND FUTURE RESEARCH

Several limitations of the present study should be acknowledged. First, the composite fabrication was performed exclusively by hand lay-up, a process that introduces operator-dependent variability in fibre distribution and void content. Industrial-scale production would require resin transfer moulding (RTM) or vacuum-assisted RTM (VARTM) processes, and the machinability characteristics may differ from those reported herein due to differences in composite homogeneity and surface quality.

Second, only unidirectional fibre orientations were investigated. Automotive interior panels commonly employ woven or randomly oriented fibre architectures, which may exhibit different machinability behaviour due to the multiplicity of fibre cutting angles encountered during tool traverse. Future studies should systematically evaluate woven bamboo fabric-reinforced composites.

Third, the current investigation evaluated machinability under dry conditions. While dry machining is common in composite processing, the thermal environment of high-speed production environments may necessitate the use of minimum quantity lubrication (MQL) or cryogenic cooling. The influence of these cooling strategies on bamboo composite machinability and surface chemistry warrants dedicated investigation.

Fourth, the long-term hygrothermal stability of machined bamboo-epoxy surfaces under automotive service environments—including cyclic humidity, elevated temperature, and UV exposure representative of tropical Nigerian conditions—has not been addressed. Future work should characterise the dimensional stability and adhesion performance of surface-treated machined edges under accelerated ageing protocols aligned with automotive environmental testing standards such as VDA 621-415.

Fifth, a lifecycle assessment (LCA) comparing the environmental footprint of bamboo-epoxy composites versus glass fibre alternatives across the full cradle-to-gate supply chain—including bamboo cultivation, fibre extraction, composite manufacture, machining waste, and end-of-life disposition—would strengthen the sustainability case presented in this study as shown in Fig. 17.

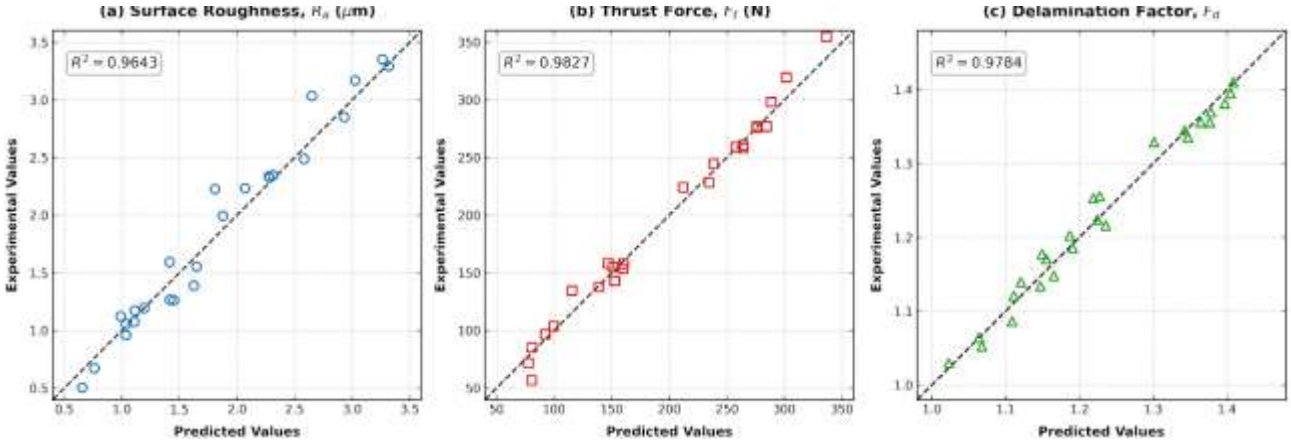


Fig. 17: *Predicted versus experimental validation results.*

CONCLUSION

This study has conducted the first systematic machinability assessment of polymer composites reinforced with indigenous Nigerian bamboo species, specifically Bambusa vulgaris and Oxytenanthera abyssinica, targeting automotive interior component production. The key conclusions are as follows:

1. Alkali treatment of bamboo fibres significantly improved tensile strength (by approximately 21% for BV and 26% for OA) and cellulose crystallinity, with BV consistently outperforming OA in both mechanical and machinability metrics due to its denser vascular bundle microstructure and higher cellulose crystallinity index.
2. The optimum fibre volume fraction was identified as 40% for both species, beyond which void-induced defects compromised tensile strength and ILSS. BV/epoxy at Vf = 40% achieved a tensile strength of 112.8 MPa and a flexural strength of 158.4 MPa.
3. ANOVA confirmed that feed rate (35.2% contribution) and cutting speed (28.4%) are the dominant factors governing surface roughness Ra, followed by fibre volume fraction (16.4%) and bamboo species (10.0%). Depth of cut exerted a statistically

significant but relatively minor influence (5.4%).
4. Minimum Ra of 1.23 µm, thrust force of 42.6 N, and delamination factor of 1.08 were achieved under the optimal parameter combination (Vc = 100 m/min, f = 0.05 mm/rev, ap = 0.5 mm, Vf = 40%, BV), satisfying automotive interior surface quality specifications.
5. The recommended machining window of Vc = 100–150 m/min, f = 0.05–0.08 mm/rev, and ap = 0.5–1.0 mm with TiAlN-coated carbide tooling enables production-viable material removal rates exceeding 2,000 mm³/min while maintaining part quality.
6. SEM analysis identified fibre pull-out, matrix micro-cracking, and fibre fracture as the principal machining damage mechanisms, with pull-out dominating at low cutting speeds and matrix smearing at high feed rates.

The results collectively establish a robust engineering basis for the deployment of Nigerian bamboo-epoxy composites as viable, sustainable, and locally sourced alternatives to glass fibre-reinforced plastics in automotive interior trim production.

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