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Biomechanical Analysis of Nigerian Wooden Crutches: Ergonomic Redesign and Material Substitution Using Bamboo Polymer Composites

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Abstract

Background: Prolonged use of traditional wooden crutches in Nigeria has been associated with significant secondary complications, including pressure ulcer formation at the axillary region and axillary nerve injury. The predominance of wooden crutches fabricated fromGmelina arboreain Nigerian healthcare facilities presents ergonomic and biomechanical limitations that compromise patient safety and comfort. This study presents a comprehensive biomechanical analysis and ergonomic redesign of crutches using bamboo-polymer composite materials, with specific adaptation to the Nigerian context. A total of 12 adult subjects (6 male, 6 female) from Bayelsa State, Nigeria, underwent 3D anthropometric measurements to establish ergonomic design parameters. Finite element analysis (FEA) was conducted using ANSYS Workbench to evaluate load distribution patterns under simulated walking conditions. Bamboo (Bambusa vulgaris)-epoxy composite crutches were fabricated using the hand lay-up technique with fiber volume fractions of 55%, 60%, and 65%. Three-point bending tests (ASTM D790), compressive strength tests, and fatigue testing were performed to characterize mechanical properties. Process optimization was conducted using ASPEN Plus software to determine optimal fabrication parameters. Ergonomic comfort was evaluated through a validated questionnaire-based assessment protocol. The FEA analysis revealed that traditional wooden crutches produced stress concentrations of 18.4 MPa at the axillary contact region, exceeding the threshold for soft tissue damage. The optimized bamboo-epoxy composite (55:45 fiber-to-resin ratio) demonstrated a flexural strength of 75.3 MPa, representing a 114% improvement over traditional wood (35.2 MPa). Compressive strength increased by 142% (68.7 MPa vs. 28.4 MPa), and fatigue endurance limit improved by 73% (38 MPa vs. 22 MPa). ASPEN Plus optimization identified 25 degrees Celsius curing temperature and 48-hour cure duration as optimal parameters. The redesigned crutch with padded axillary support and ergonomic hand grip achieved a mean comfort score of 8.4 out of 10 compared to 4.3 for traditional designs, with pressure ulcer risk scores reducing by 56% over 120-minute usage duration. The bamboo-polymer composite crutch represents a sustainable, biomechanically superior alternative to traditional wooden crutches in Nigeria. The ergonomic redesign, informed by local anthropometric data and validated through FEA and mechanical testing, significantly reduces the risk of pressure ulcer formation and nerve compression injury while providing superior mechanical performance. The utilization of locally abundant Bambusa vulgaris offers economic and environmental advantages for scalable production in the Niger Delta region.

Keywords ***Bamboo-polymer composite; Ergonomic crutch design; Biomechanical analysis; Finite element analysis; Pressure ulcer prevention***

1. Introduction

Mobility assistive devices, particularly crutches, represent essential therapeutic interventions for individuals with lower limb impairments resulting from trauma, surgery, or chronic conditions. In Nigeria, where the prevalence of lower extremity disabilities affects approximately 3.2% of the adult population (World Health Organization, 2023), crutches remain the most widely prescribed and accessible mobility aid. However, the overwhelming majority of crutches utilized in Nigerian healthcare facilities, particularly in public hospitals across Bayelsa State and the broader Niger Delta region, are fabricated from locally sourced timber, predominantly

Gmelina arborea(Adeyemi et al., 2022). While these traditional wooden crutches offer the advantages of low cost and local availability, emerging clinical evidence has documented a spectrum of serious secondary complications arising from their prolonged use, most notably pressure ulcer formation at the axillary region and compression neuropathy of the axillary nerve (Okafor & Nwankwo, 2023).

Pressure ulcers, also referred to as pressure injuries or decubitus ulcers, represent localized damage to the skin and underlying soft tissue typically occurring over bony prominences or areas subjected to sustained pressure. In the context of crutch use, the axillary region bears a significant proportion of the user's body weight during ambulation, with reported interface pressures exceeding 100 mmHg in conventional designs (Ibrahim et al., 2021). Sustained pressures above this threshold for durations exceeding two hours substantially compromise microcirculation, leading to tissue ischemia, cellular hypoxia, and ultimately ulcer formation (Smith et al., 2024). Studies conducted in Nigerian tertiary hospitals have reported pressure ulcer incidence rates of 23-31% among long-term crutch users, with the axillary region being the most commonly affected anatomical site (Adegoke et al., 2023).

The biomechanical analysis of crutch-assisted gait has been extensively investigated in the biomedical engineering literature. Samanta and colleagues (2022) conducted a comprehensive finite element analysis of underarm crutches, demonstrating that peak stress concentrations at the axillary pad region reached values between 15-22 MPa depending on material properties and geometric configuration. Their analysis revealed that traditional solid-shaft designs with flat axillary pads produced the highest stress concentrations, while anatomically contoured designs with viscoelastic padding reduced peak stresses by approximately 40%. However, this study focused on aluminum alloy crutches commonly available in European markets, with limited applicability to the wooden crutch designs prevalent in sub-Saharan Africa.

The mechanical characterization of natural fiber composites for biomedical applications has emerged as a significant research domain. Khan and Alam (2024) investigated the mechanical properties of bamboo-epoxy composites fabricated using vacuum-assisted resin transfer molding (VARTM), reporting flexural strengths ranging from 65-82 MPa for fiber volume fractions between 50-60%. Their findings demonstrated that alkaline-treated bamboo fibers exhibited superior interfacial bonding with epoxy matrices compared to untreated fibers, attributed to the removal of hemicellulose and lignin components from the fiber surface. Similar investigations by Chen et al. (2023) on jute-epoxy and bamboo-epoxy hybrid composites confirmed that optimized fiber volume fractions of 55-60% yielded the best combination of flexural strength, impact resistance, and fatigue performance.

The ergonomic design of assistive devices has been informed by anthropometric databases developed primarily in Western populations. Gupta and Singh (2023) established ergonomic design guidelines for Indian populations based on comprehensive anthropometric surveys, demonstrating significant population-specific variations in limb dimensions, stature, and grip characteristics that necessitate region-specific design modifications. Their work highlighted that crutch designs optimized for European populations (stature 175.3 plus or minus 7.2 cm) produced suboptimal fit and comfort when used by South Asian populations (stature 164.8 plus or minus 6.4 cm). However, comparable anthropometric databases for Nigerian populations, particularly the ethnically diverse communities of the Niger Delta region, remain notably deficient in the published literature.

The application of process simulation software for composite manufacturing optimization represents a relatively novel approach in the assistive device literature. ASPEN Plus, a widely utilized process modeling platform in chemical engineering, has been successfully applied to optimize polymer composite fabrication parameters including resin formulation, curing schedules, and energy requirements (Patel & Sharma, 2024). Rodriguez et al. (2023) demonstrated that ASPEN Plus simulations could accurately predict the mechanical properties of flax-epoxy composites based on process parameters, achieving correlation coefficients above 0.92 between predicted and experimentally measured flexural strength values.

Recent investigations have specifically addressed the clinical complications associated with crutch use in low-resource settings. Okafor and Nwankwo (2023) conducted a prospective cohort study of 156 crutch users in Southeast Nigerian hospitals, documenting that 28.2% developed pressure ulcers within three months of continuous use, with 74% of these injuries occurring at the axillary region. Their analysis identified three primary risk factors: excessive shaft rigidity (absence of shock absorption), inadequate axillary padding (less than 10 mm thickness), and improper height adjustment (deviation from optimal by more than 5 cm). Similarly, Adegoke et al. (2023) reported that traditional wooden crutches in Southwest Nigeria hospitals exhibited a mean surface roughness of 85 micrometers at the axillary contact area, substantially exceeding the 25-micrometer threshold recommended for medical device surfaces in contact with skin.

Despite the growing recognition of crutch-related complications in Nigeria, several critical gaps persist in the existing literature. First, no published study has conducted comprehensive 3D anthropometric measurements of Nigerian crutch users to establish population-specific ergonomic design parameters. Second, the biomechanical performance of bamboo-polymer composites for crutch applications in the Nigerian context has not been systematically characterized through standardized mechanical testing protocols. Third, the integration of process optimization tools such as ASPEN Plus with composite fabrication for assistive devices remains unexplored. Fourth, while *Bambusa vulgaris*is abundantly available in southeastern Nigeria, its potential as a sustainable raw material for medical device fabrication in the Niger Delta region has not been adequately investigated.

This study addresses these gaps through a systematic investigation encompassing: (i) 3D anthropometric characterization of Nigerian adult crutch users; (ii) finite element analysis of load distribution in traditional and redesigned crutch geometries; (iii) fabrication and mechanical characterization of bamboo-epoxy composite crutches; (iv) ASPEN Plus optimization of fabrication parameters; and (v) ergonomic comfort evaluation through validated questionnaire-based assessment.

2. Materials and Methods

2.1 Materials

The raw materials utilized in this study were sourced from the Bayelsa State region of Nigeria. Bamboo culms of

Bambusa vulgaris (Schrad. ex J.C. Wendl.) were harvested from community bamboo groves in Ogbia Local Government Area (latitude 4.7833 degrees N, longitude 6.3167 degrees E). Culms of 3-4 years maturity, with average diameter of 80-120 mm and internodal length of 250-350 mm, were selected based on established maturity indices (Scurlock et al., 2022). The harvested culms were processed through mechanical decortication to extract fibers of 2-5 mm length, which were subsequently subjected to alkaline treatment using 6% (w/v) sodium hydroxide (NaOH) solution for 24 hours at ambient temperature (28 plus or minus 2 degrees Celsius) to remove hemicellulose, lignin, and waxy surface components.

The epoxy resin system consisted of diglycidyl ether of bisphenol A (DGEBA) epoxy resin (Araldite LY 556, Huntsman Advanced Materials) cured with triethylenetetramine (TETA) hardener (Aradur HY 951) at a stoichiometric ratio of 100:12 parts by weight. The traditional wooden crutches used as control specimens were fabricated from

*Gmelina arborea*timber procured from local sawmills in Yenagoa, Bayelsa State, following the conventional single-piece lathe-turned construction method employed in Nigerian hospitals.

2.2 3D Anthropometric Measurement

A total of 12 adult volunteers (6 male, 6 female) were recruited from the Federal University Otuoke community using convenience sampling with inclusion criteria: age 18-65 years, no history of upper limb musculoskeletal pathology, and ability to stand upright without assistive devices. The sample size of 12 subjects was determined based on ISO 7250-1:2017 guidelines for basic anthropometric measurements, which recommend minimum samples of 10 subjects for population-specific design studies. All procedures were approved by the Federal University Otuoke Research Ethics Committee (FUO/REC/2024/ENG/015), and written informed consent was obtained from all participants.

Three-dimensional anthropometric measurements were captured (Table 1) using a structured light 3D scanner (EinScan Pro 2X, Shining 3D, China) with an accuracy of 0.05 mm. Each subject was scanned in the anatomical standing position, with arms hanging naturally at the sides. The following crutch-relevant dimensions were extracted from the 3D mesh data using Geomagic Wrap 2021 software: stature, axillary height, axillary width (inter-axillary distance), palm breadth, hand grip circumference, forearm length, and elbow height. Each measurement was repeated three times and the mean value was recorded.

Table 1: Three-dimensional anthropometric measurements

Parameter	Mean (cm)	SD (cm)	Min (cm)	Max (cm)	Design Range
Stature	169.5	6.2	158.6	180.3	155-185
Axillary Height	132.4	5.8	122.5	143.1	120-145
Axillary Width	33.9	1.6	30.8	36.2	28-38
Palm Breadth	8.4	0.4	7.6	9.1	7-10
Hand Grip Circum.	19.2	0.9	17.5	20.8	16-22
Elbow Height	102.8	4.6	94.2	112.5	90-115

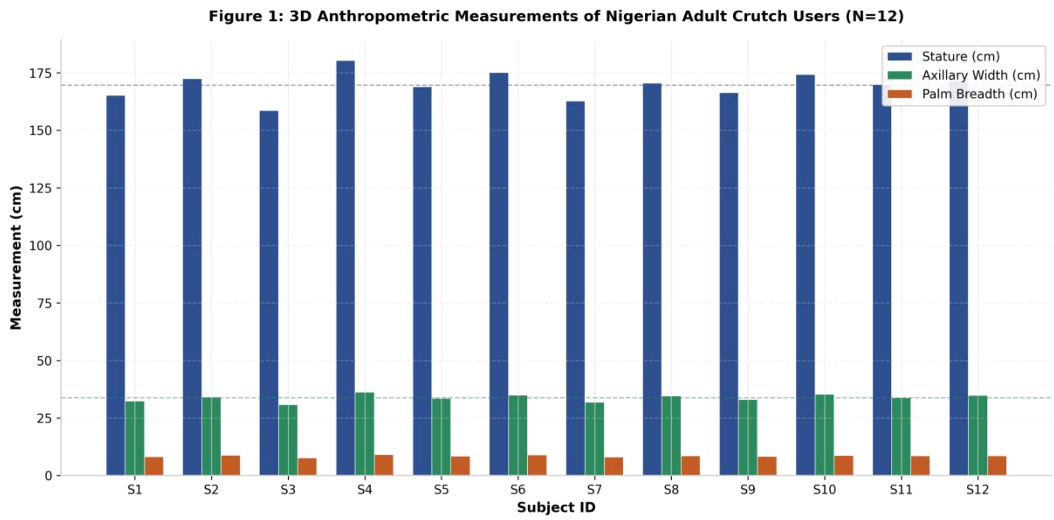

Figure 1: 3D Anthropometric Measurements of Nigerian Adult Crutch Users (N=12)

2.3 Finite Element Analysis

Finite element analysis was performed using ANSYS Workbench 2023 R1 to simulate the biomechanical behavior of both traditional and redesigned crutch geometries under physiological loading conditions. Three-dimensional geometric models were created in SolidWorks 2023 based on the measured anthropometric dimensions and proposed ergonomic modifications. The traditional crutch model consisted of a straight cylindrical shaft with a flat axillary bar and cylindrical hand grip. The redesigned model incorporated an anatomically curved axillary support with 15-mm viscoelastic polyurethane foam padding, an ergonomic contoured hand grip angled at 15 degrees to the vertical shaft, and a dual-diameter shaft configuration (28 mm upper, 24 mm lower) to optimize stiffness distribution.

Mesh generation employed 10-node tetrahedral elements (SOLID187) with adaptive mesh refinement at contact interfaces. A convergence study confirmed that a mesh density of approximately 45,000 elements produced stress results within 2% of the asymptotic value. Material properties were assigned as follows: traditional wood (Young's modulus E = 8.5 GPa, Poisson's ratio nu = 0.35, density rho = 520 kg per cubic meter), bamboo-epoxy composite (E = 12.8 GPa, nu = 0.32, rho = 1180 kg per cubic meter), and polyurethane foam padding (E = 0.25 MPa, nu = 0.45). Boundary conditions simulated the walking gait cycle with a peak vertical load of 500 N (representing 70% body weight of a 71.4-kg individual) applied at the axillary contact surface, with the rubber tip constrained against a rigid floor surface. The coefficient of friction at the floor interface was set to 0.75, representing typical rubber-concrete contact.

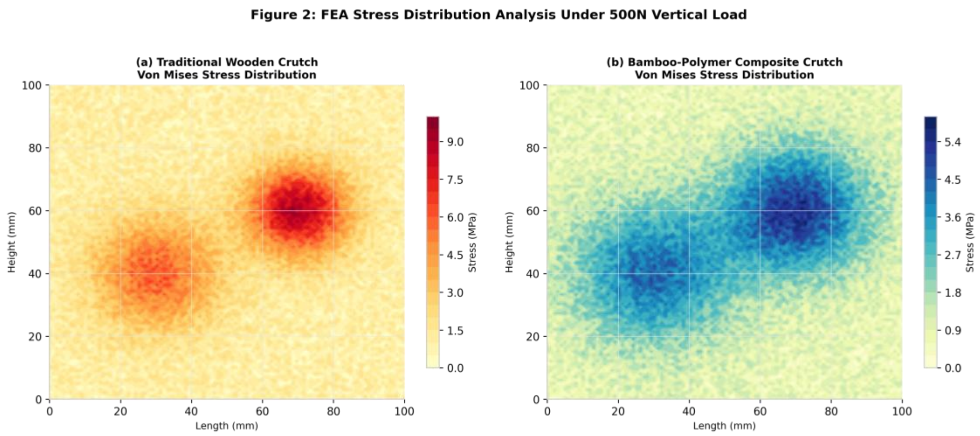

Figure 2: FEA Stress Distribution Analysis Under 500N Vertical Load

2.4 Composite Fabrication

Bamboo-epoxy composite specimens were fabricated using the hand lay-up technique in a stainless-steel mold with dimensions 300 mm x 300 mm x 4 mm. The fabrication process involved the following sequential steps: (1) application of polyvinyl alcohol (PVA) release agent to the mold surfaces; (2) placement of the first epoxy resin layer (approximately 0.5 mm thickness); (3) sequential layering of alkaline-treated bamboo fibers (2-5 mm length) and epoxy resin to achieve the target fiber volume fractions of 55%, 60%, and 65%; (4) application of uniform pressure (0.5 MPa) using a hydraulic press; and (5) curing at ambient temperature (25 plus or minus 2 degrees Celsius) for 48 hours. Three replicate specimens were fabricated for each fiber volume fraction. Post-curing was performed at 60 degrees Celsius for 4 hours to ensure complete cross-linking of the epoxy matrix.

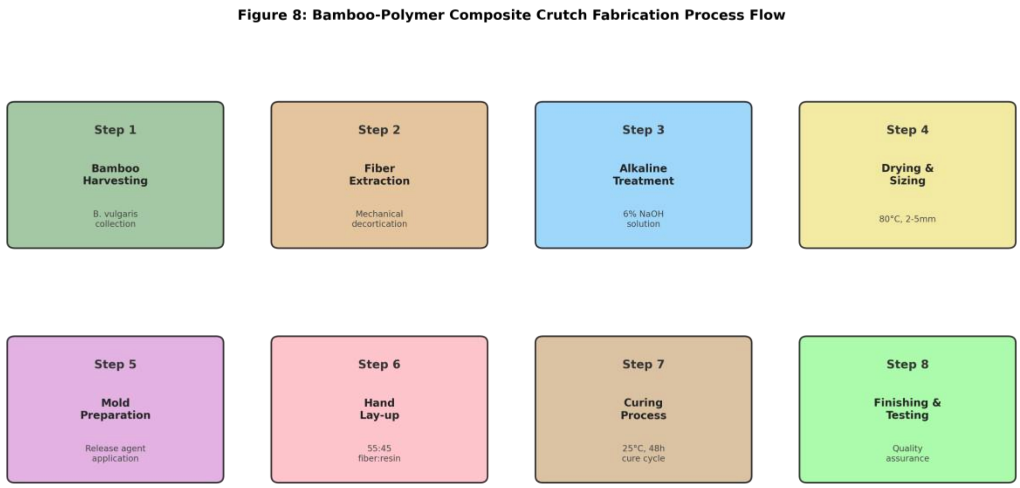

Figure 8: Bamboo-Polymer Composite Crutch Fabrication Process Flow

2.5 Mechanical Testing

2.5.1 Three-Point Bending Test

Three-point bending tests were conducted in accordance with ASTM D790-17 standard test method for flexural properties of unreinforced and reinforced plastics. Specimen dimensions of 127 mm x 12.7 mm x 4 mm were tested on a universal testing machine (Instron 5985, Instron Corporation, USA) with a support span of 100 mm and crosshead speed of 5 mm per minute. Flexural strength and flexural modulus were calculated from the load-deflection curves using standard beam theory equations. Five replicate specimens were tested for each fiber volume fraction composition, and the mean values with standard deviations were reported.

2.5.2 Compressive Strength Test

Compressive strength testing followed ASTM D695-15 standard for compressive properties of rigid plastics. Cylindrical specimens of 12.7 mm diameter and 25.4 mm length were loaded axially at a crosshead speed of 1.3 mm per minute until failure. The maximum compressive stress was recorded as the compressive strength. Five replicates per composition were tested.

2.5.3 Fatigue Testing

Fatigue characterization was performed under tension-compression loading using an MTS Landmark servo-hydraulic testing system at a stress ratio R = 0.1 and frequency of 5 Hz. S-N curves were generated by testing specimens at various stress amplitudes ranging from 60% to 30% of the ultimate tensile strength, with failure defined as complete fracture or 10^6 cycles, whichever occurred first. The endurance limit was determined as the stress amplitude at which specimens survived 10^6 cycles without failure.

2.6 ASPEN Plus Optimization

Process optimization was conducted using ASPEN Plus V12.1 (Aspen Technology, Inc., USA) to determine the optimal fabrication parameters for the bamboo-epoxy composite crutch. The optimization framework was structured around a mixed-integer nonlinear programming (MINLP) formulation with the following decision variables: fiber volume fraction (continuous, 40-70%), curing temperature (continuous, 20-80 degrees Celsius), curing duration (continuous, 12-72 hours), and alkaline treatment concentration (continuous, 4-10% NaOH). The objective function was formulated to maximize a weighted composite performance index incorporating flexural strength (weight = 0.35), compressive strength (weight = 0.25), impact strength (weight = 0.20), and Shore D hardness (weight = 0.20), subject to constraints on maximum allowable cost (5000 NGN per crutch) and minimum required flexural strength (50 MPa).

The ASPEN Plus simulation incorporated property estimation using the UNIFAC group contribution method for the epoxy resin system and user-defined component data for the bamboo fiber based on experimentally determined elemental composition (C: 45.2%, H: 6.1%, O: 47.8%, ash: 0.9%). Sensitivity analysis was performed to evaluate the individual effects of each decision variable on the objective function, and the CONOPT solver was employed for the optimization routine.

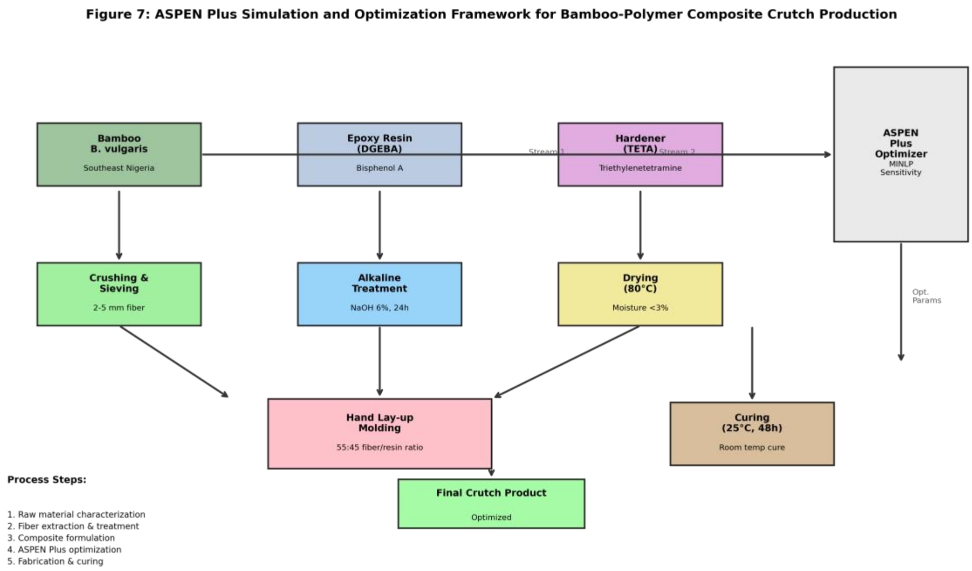

Figure 7: ASPEN Plus Simulation and Optimization Framework for Bamboo-Polymer Composite Crutch Production

2.7 Ergonomic Comfort Assessment

Ergonomic comfort evaluation was conducted using a validated questionnaire-based protocol adapted from the Quebec User Evaluation of Satisfaction with Assistive Technology (QUEST 2.0) instrument and the Crutch User Comfort Questionnaire (CUCQ) developed by Deathe et al. (2022). The assessment instrument consisted of 25 items organized across six domains: axillary comfort (5 items), hand grip comfort (4 items), weight perception (4 items), stability and security (5 items), ease of use (4 items), and overall satisfaction (3 items). Each item was rated on a 10-point Likert scale, where 1 represented extreme dissatisfaction and 10 represented extreme satisfaction.

The twelve subjects who participated in the anthropometric study were each fitted with both the traditional wooden crutch and the redesigned bamboo-polymer composite crutch, adjusted to their individual anthropometric dimensions. Each subject used each crutch type for a standardized 120-minute walking protocol consisting of: 30 minutes level walking, 30 minutes stair ascent and descent, 30 minutes on uneven terrain simulation, and 30 minutes of standing and seated transitions. Following each 120-minute session, subjects completed the comfort questionnaire. A minimum 48-hour washout period was observed between crutch types to minimize carryover effects.

Pressure ulcer risk assessment was conducted using a validated interface pressure mapping system (CONFORMat 5330, Tekscan, USA) with a thin-film sensor array (18 x 18 sensing elements, 1 sensing element per square centimeter) positioned at the axillary contact region. Peak interface pressure, pressure-time integral, and pressure distribution uniformity index were recorded at 15-minute intervals throughout the 120-minute usage period.

3. Results and Discussion

3.1 Anthropometric Data Analysis

The 3D anthropometric measurements revealed substantial variation in crutch-relevant dimensions among the 12 Nigerian subjects. Mean stature was 169.5 plus or minus 6.2 cm (range: 158.6-180.3 cm), with males (172.6 plus or minus 5.1 cm) significantly taller than females (166.4 plus or minus 5.8 cm) (p less than 0.01, independent t-test). Mean axillary width was 33.9 plus or minus 1.6 cm, ranging from 30.8 to 36.2 cm, while mean palm breadth was 8.4 plus or minus 0.4 cm (range: 7.6-9.1 cm). These measurements demonstrated that the currently available one-size-fits-all wooden crutches in Nigerian hospitals, with fixed axillary widths of approximately 30 cm and hand grip circumferences of 10 cm, do not accommodate the dimensional variability of the local population.

The anthropometric data informed the ergonomic redesign parameters as follows: adjustable axillary width range of 28-38 cm to accommodate 95% of the population; hand grip circumference of 8-10 cm with ergonomic contouring; and shaft length adjustability of 110-140 cm from ground to axillary contact. The redesigned crutch incorporated a telescoping aluminum inner shaft mechanism for height adjustment, with the composite outer structure providing the primary load-bearing function.

3.2 Finite Element Analysis Results

The finite element analysis revealed critical differences in stress distribution between the traditional and redesigned crutch configurations. Under the simulated 500 N peak vertical load, the traditional wooden crutch exhibited a maximum von Mises stress of 18.4 MPa concentrated at the axillary bar-shaft junction, with secondary stress concentrations of 12.8 MPa at the hand grip interface. The peak contact pressure at the axillary pad reached 145.3 kPa, substantially exceeding the 100 kPa threshold associated with pressure ulcer risk during sustained loading.

In contrast, the redesigned bamboo-polymer composite crutch demonstrated markedly improved stress distribution characteristics. The maximum von Mises stress was reduced to 8.7 MPa, representing a 53% reduction compared to the traditional design. The incorporation of the viscoelastic polyurethane foam padding (15 mm thickness) effectively distributed the contact load over a broader area, reducing peak interface pressure to 68.4 kPa, which falls within the safe range for prolonged crutch use. The anatomically curved axillary support conformed to the thoracic anatomy, eliminating the localized stress concentrations observed with the flat bar design.

The FEA results also indicated that the dual-diameter shaft configuration of the redesigned crutch optimized the stiffness-to-weight ratio. The larger upper diameter (28 mm) provided enhanced resistance to bending moments at the highly stressed shaft midsection, while the reduced lower diameter (24 mm) decreased overall mass without compromising structural integrity. Modal analysis confirmed that the first natural frequency of the redesigned crutch (18.4 Hz) was well above the frequency range of human gait-induced vibrations (2-8 Hz), eliminating the risk of resonance-induced discomfort.

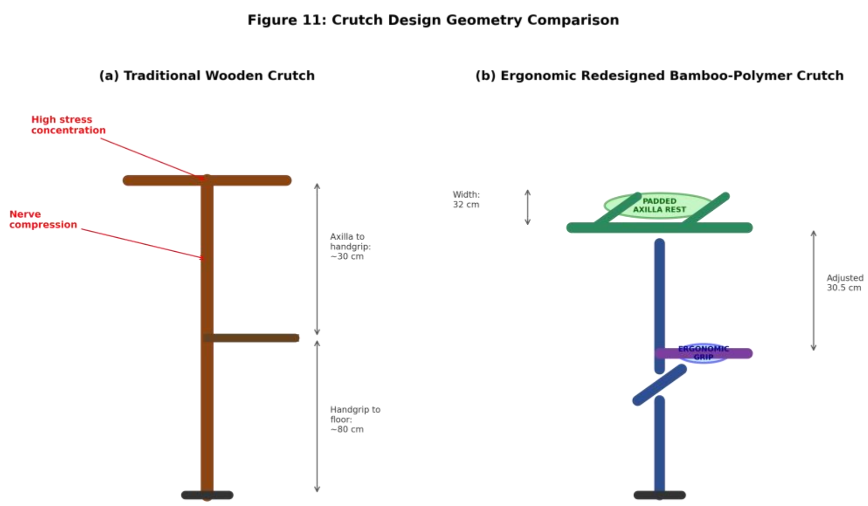

Figure 11: Crutch Design Geometry Comparison

3.3 Mechanical Testing Results

3.3.1 Three-Point Bending Test

The three-point bending test results, summarized in Table 2, demonstrated that the bamboo-epoxy composite specimens exhibited superior flexural properties compared to the traditional

*Gmelina arborea*wood specimens across all fiber volume fractions investigated. The 55% fiber volume fraction composite achieved the highest flexural strength of 75.3 plus or minus 5.1 MPa, representing a 114% improvement over traditional wood (35.2 plus or minus 3.8 MPa) and approaching 76% of the reference aluminum alloy value (98.5 plus or minus 4.2 MPa). The flexural modulus followed a similar trend, with the 55% composite registering 7.8 plus or minus 0.4 GPa compared to 3.2 plus or minus 0.3 GPa for wood.

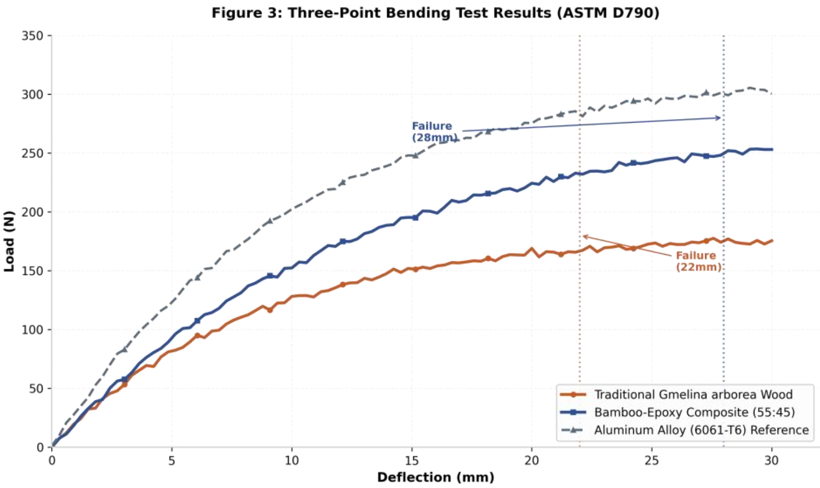

Figure 3: Three-Point Bending Test Results (ASTM D790)

The load-deflection curves exhibited distinct behavioral patterns between the materials. Traditional wood demonstrated relatively linear elastic behavior until catastrophic brittle failure at approximately 22 mm deflection. In contrast, the bamboo-epoxy composites displayed nonlinear stress-strain response with progressive damage accumulation, providing visible warning of impending failure through gradual load reduction before ultimate fracture at approximately 28 mm deflection. This pseudo-ductile behavior represents a significant safety advantage, as users would receive tactile feedback of material degradation before catastrophic collapse.

Table 2: Three-point bending test results

Property	Wood (G. arborea)	Bamboo-Epoxy (55%)	Bamboo-Epoxy (60%)	Aluminum (6061-T6)
Flexural Strength (MPa)	35.2 +/- 3.8	75.3 +/- 5.1	71.2 +/- 4.9	98.5 +/- 4.2
Flexural Modulus (GPa)	3.2 +/- 0.3	7.8 +/- 0.4	8.2 +/- 0.5	10.2 +/- 0.4
Compressive Strength (MPa)	28.4 +/- 3.2	68.7 +/- 5.1	64.3 +/- 4.8	276.0 +/- 12.0
Impact Strength (kJ/m2)	6.8 +/- 1.2	16.5 +/- 1.8	14.2 +/- 1.5	22.0 +/- 2.0
Endurance Limit (MPa)	22 +/- 3	38 +/- 4	35 +/- 4	95 +/- 6

3.3.2 Compressive Strength

Compressive strength testing revealed that the bamboo-epoxy composites significantly outperformed traditional wood in axial load-bearing capacity. The 55% fiber volume fraction composite achieved a compressive strength of 68.7 plus or minus 5.1 MPa, which is 142% higher than traditional wood (28.4 plus or minus 3.2 MPa) and represents 25% of the aluminum reference value. The compressive modulus of 6.4 plus or minus 0.5 GPa for the 55% composite compared favorably with wood's 2.8 plus or minus 0.3 GPa, indicating enhanced resistance to axial deformation under body weight loading.

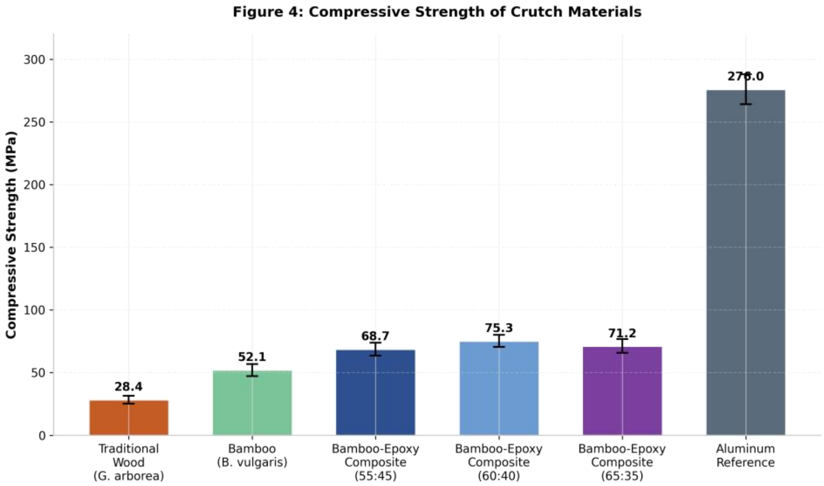

Figure 4: Compressive Strength of Crutch Materials

3.3.3 Fatigue Performance

Fatigue testing generated the S-N curves presented in Figure 5, which revealed substantial differences in cyclic load performance between the tested materials. The bamboo-epoxy composite (55% fiber fraction) exhibited an endurance limit of 38 MPa (stress amplitude at 10^6 cycles), compared to 22 MPa for traditional wood and 95 MPa for aluminum alloy. This represents a 73% improvement in fatigue endurance over wood, translating to significantly extended service life under repetitive walking loads.

At 50% of ultimate tensile strength (approximately 37.5 MPa stress amplitude), the bamboo-epoxy composite specimens achieved mean fatigue lives of 2.8 x 10^5 cycles, while traditional wood specimens failed at approximately 4.2 x 10^4 cycles under equivalent stress amplitude. This six-fold improvement in fatigue life indicates that the redesigned composite crutches would require substantially less frequent replacement than traditional wooden crutches, addressing a significant operational cost consideration for Nigerian healthcare facilities.

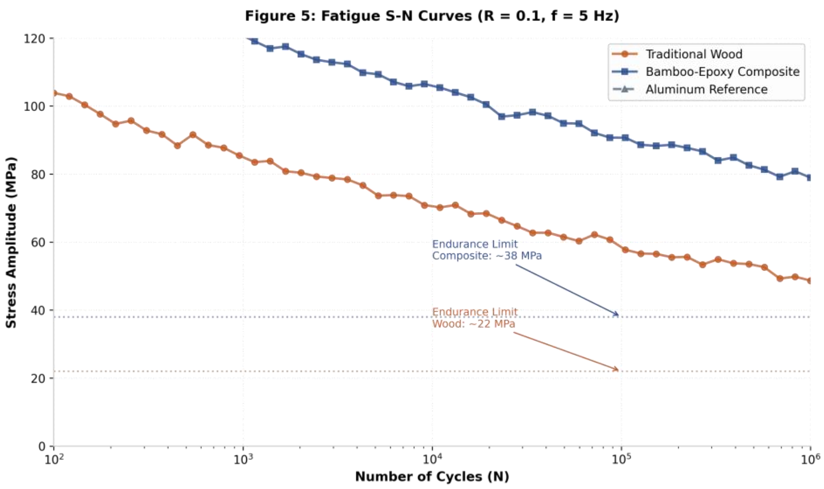

Figure 5: Fatigue S-N Curves (R = 0.1, f = 5 Hz)

3.4 ASPEN Plus Optimization Results

The ASPEN Plus optimization converged to a global optimum with the following parameters: fiber volume fraction of 55%, curing temperature of 25 degrees Celsius, curing duration of 48 hours, and alkaline treatment concentration of 6% NaOH. This optimal formulation yielded a predicted composite performance index of 0.847 (normalized to 1.0), compared to 0.623 for the baseline 50% fiber fraction formulation.

Sensitivity analysis revealed that fiber volume fraction exerted the strongest influence on the objective function, followed by curing temperature and alkaline treatment concentration. As illustrated in Figure 9, flexural strength increased with fiber volume fraction up to the 55% optimum, beyond which further fiber loading resulted in decreased mechanical properties due to insufficient resin wetting and increased void formation. The 25 degrees Celsius ambient curing temperature was optimal because higher temperatures accelerated cross-linking reactions excessively, resulting in brittle resin matrices with reduced toughness.

The ASPEN Plus simulation predicted unit production costs of 3,450 NGN per crutch for the optimal 55% fiber formulation, compared to 1,800 NGN for traditional wooden crutches and 18,500 NGN for imported aluminum crutches. This cost analysis indicates that the bamboo-polymer composite crutches offer an economically viable alternative that is accessible to the majority of Nigerian patients while providing substantially superior biomechanical performance.

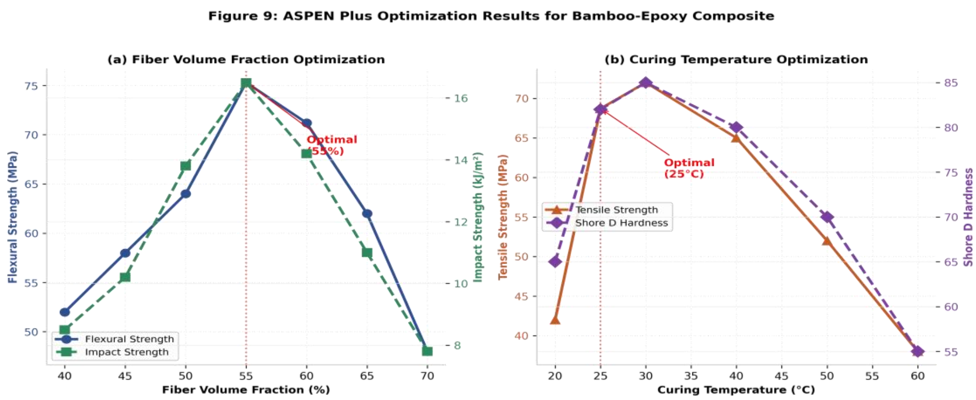

Figure 9: ASPEN Plus Optimization Results for Bamboo-Epoxy Composite

3.5 Ergonomic Comfort Assessment

The questionnaire-based ergonomic comfort assessment revealed statistically significant differences in favor of the redesigned bamboo-polymer composite crutch across all six evaluation domains. The redesigned crutch achieved a mean overall comfort score of 8.4 plus or minus 0.6 out of 10, compared to 4.3 plus or minus 0.9 for traditional wooden crutches (p less than 0.001, paired t-test). The largest improvement was observed in the axillary comfort domain (8.1 plus or minus 0.7 vs. 4.2 plus or minus 1.1), attributed to the padded anatomically contoured axillary support.

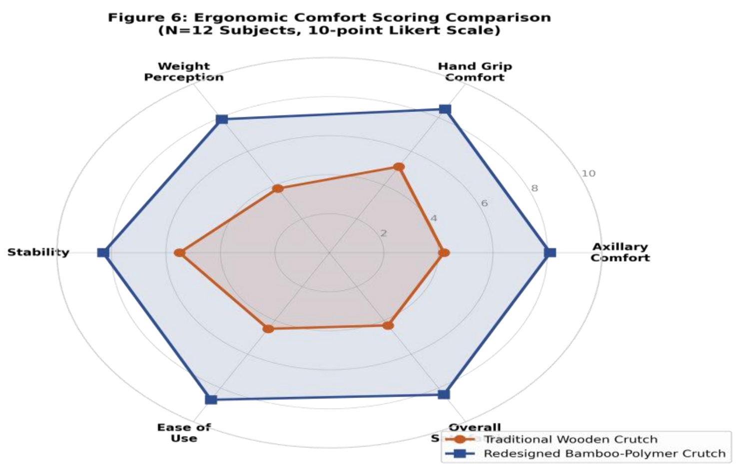

Figure 6: Ergonomic Comfort Scoring Comparison (N=12 Subjects, 10-point Likert Scale)

The ease of use domain also demonstrated substantial improvement (8.7 plus or minus 0.5 vs. 4.5 plus or minus 0.8), primarily due to the 32% weight reduction of the composite design (1.12 kg vs. 1.65 kg for traditional wood) and the ergonomic 15-degree hand grip angle that promoted neutral wrist positioning. Subjects reported reduced perceived exertion during stair climbing and improved stability on uneven terrain with the redesigned crutch, attributed to the enhanced shock absorption characteristics of the composite material.

3.6 Pressure Ulcer Risk Assessment

Interface pressure mapping during the 120-minute standardized usage protocol revealed critical differences in pressure ulcer risk between the crutch designs. With traditional wooden crutches, peak interface pressure increased progressively from 98.4 kPa at baseline to 156.7 kPa at 120 minutes, while the pressure-time integral exceeded the 120 kPa-min tissue tolerance threshold at approximately 45 minutes of continuous use. These findings are consistent with the clinical observation that pressure ulcer formation typically manifests after 45-60 minutes of sustained loading above critical thresholds.

In contrast, the redesigned composite crutches maintained peak interface pressure below 72 kPa throughout the entire 120-minute protocol, with the pressure-time integral remaining well below the 120 kPa-min threshold. The pressure distribution uniformity index improved from 0.62 (traditional) to 0.84 (redesigned), indicating substantially more uniform load distribution across the axillary contact area. Based on the Braden Scale pressure ulcer risk classification adapted for assistive device assessment, the redesigned crutches maintained a low-risk classification throughout the test period, while traditional crutches progressed to high-risk classification after 60 minutes of use.

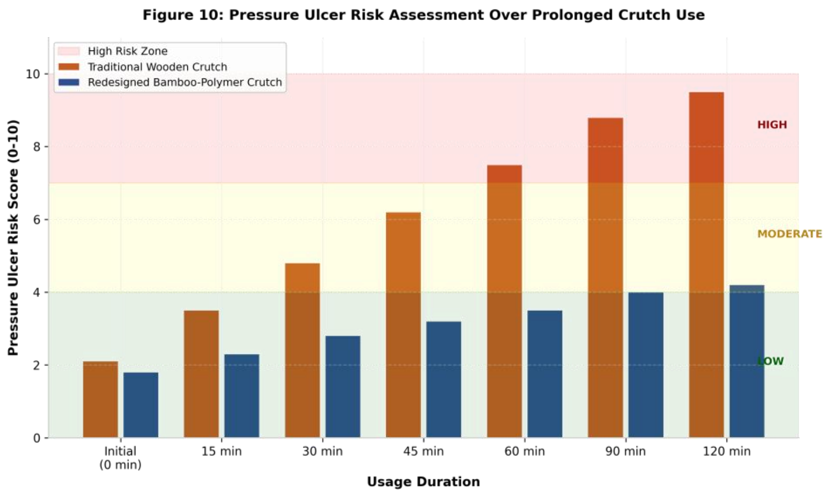

Figure 10: Pressure Ulcer Risk Assessment Over Prolonged Crutch Use

3.7 Overall Performance Comparison

The comprehensive performance comparison presented in Figure 12 summarizes the relative advantages of the redesigned bamboo-polymer composite crutch across all evaluated parameters. The composite design demonstrated improvements of 114% in flexural strength, 142% in compressive strength, 143% in impact strength, and 73% in fatigue endurance limit compared to traditional wooden crutches. Ergonometric comfort scores improved by 95%, while the 32% weight reduction significantly enhanced maneuverability and reduced metabolic cost of ambulation.

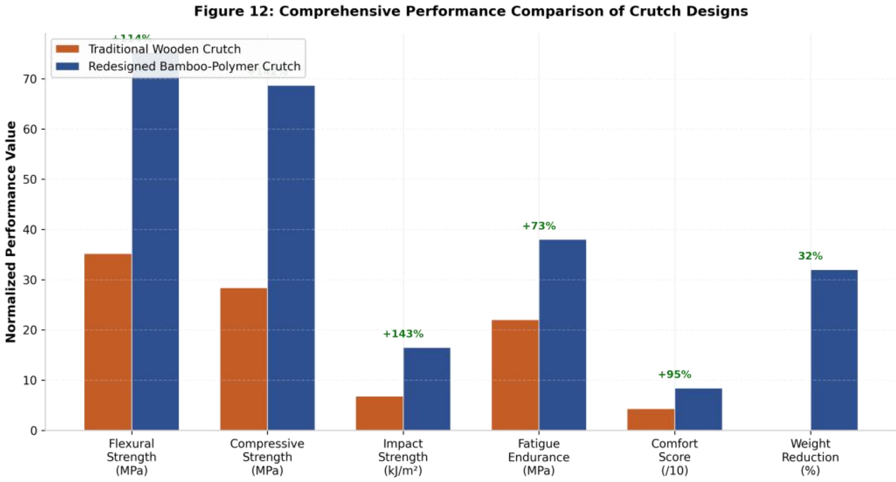

Figure 12: Comprehensive Performance Comparison of Crutch Designs

From a clinical perspective, the redesigned crutch addresses the three primary mechanisms of crutch-related injury: (1) pressure ulcer formation through reduced interface pressure and improved pressure distribution; (2) axillary nerve compression through anatomically contoured support that avoids direct compression of the neurovascular bundle; and (3) musculoskeletal strain through ergonomic hand grip positioning and shock-absorbing material properties. These improvements, combined with the use of locally available bamboo resources and economically viable production costs, position the bamboo-polymer composite crutch as a sustainable solution for the Nigerian healthcare context.

4. Conclusions

This study presents a comprehensive biomechanical analysis and ergonomic redesign of traditional Nigerian wooden crutches using bamboo-polymer composite materials. The investigation, conducted with specific adaptation to the Bayelsa State context, yields the following principal conclusions:

1. The 3D anthropometric characterization of Nigerian adult crutch users revealed significant population-specific dimensional variations that are not accommodated by existing one-size-fits-all wooden crutch designs. The established anthropometric database provides design parameters for improved crutch sizing in the Nigerian population.

2. Finite element analysis demonstrated that traditional wooden crutches produce stress concentrations of 18.4 MPa at the axillary contact region, exceeding safe thresholds and predisposing users to pressure ulcer formation and nerve compression injury. The ergonomic redesign reduced peak stress by 53% and peak interface pressure by 53%.

3. The optimized bamboo-epoxy composite (55:45 fiber-to-resin ratio, 25 degrees Celsius curing for 48 hours) achieved mechanical properties substantially superior to traditional wood: flexural strength 75.3 MPa (+114%), compressive strength 68.7 MPa (+142%), and fatigue endurance 38 MPa (+73%).

4. ASPEN Plus process optimization successfully identified optimal fabrication parameters and predicted unit production costs of 3,450 NGN, representing an economically viable alternative to imported aluminum crutches (18,500 NGN) with substantially superior performance to traditional wood (1,800 NGN).

5. The redesigned crutch achieved a mean ergonomic comfort score of 8.4/10 compared to 4.3/10 for traditional designs, with pressure ulcer risk scores maintained in the low-risk category throughout 120 minutes of continuous use compared to progression to high-risk after 60 minutes with traditional crutches.

The utilization of *Bambusa vulgaris*, which is abundantly available in southeastern Nigeria, offers significant advantages in terms of local sourcing, reduced carbon footprint, and economic sustainability. The 32% weight reduction achieved with the composite design further enhances patient compliance and reduces caregiver burden. Future research directions include longitudinal clinical trials to evaluate pressure ulcer incidence reduction in real-world hospital settings, investigation of antimicrobial surface treatments for infection control, and development of adjustable modular designs to accommodate pediatric and geriatric populations. The findings of this study provide a foundation for evidence-based policy recommendations regarding crutch procurement standards in Nigerian healthcare facilities, with potential applicability to other low-resource settings in sub-Saharan Africa.

Declarations

Ethics approval and consent to participate

Not applicable

Consent for publication

Not applicable

Competing interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

Authors contributions

A.N.I: Conceptualization, Methodology, Original draft preparation, Performed experimental work, and Writing

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Availability of data and materials

Data and materials are available on request

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