



DESIGN, FABRICATION, AND FIELD EVALUATION OF A COST-EFFECTIVE PEG-TOOTH RICE THRESHER FOR SMALLHOLDER FARMERS IN SOUTH-EASTERN NIGERIA

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ABSTRACT

Rice threshing remains a critical bottleneck in Sub-Saharan Africa's post-harvest chain, with manual methods contributing to 15-20% grain losses. This study presents the systematic design, fabrication, and preliminary evaluation of a small-scale peg-tooth rice thresher for smallholder farmers in south-eastern Nigeria. Using a 4.5 kW gasoline engine, the machine features a 400 × 600 mm threshing drum with 48 peg-teeth (peg-tip velocity: 23.46 m·s⁻¹ at 800 rpm), a 120° concave wrap, and a vibratory cleaning sieve. Preliminary testing on FARO 44 paddy (150 kg, 17-22% moisture content) achieved threshing a mean threshing efficiency of 94.58% (range: 94.47–94.76%) cleaning efficiency of 95.07%, grain damage of 2.16% ± 0.13 and throughput of 455.4 kg·h⁻¹. Fabrication cost was ₦438,000 (~\$290), demonstrating economic viability for cooperative ownership. The results indicate that locally fabricated threshers can meet international performance standards while remaining affordable and maintainable in rural Nigerian settings. Future work will focus on multi-variable optimization of feed rate, concave clearance, and drum speed under controlled moisture conditions.

Keywords: *Rice thresher, Peg-tooth drum, Post-harvest mechanization, Threshing efficiency, Smallholder farmers, Nigeria*

INTRODUCTION

Rice is a global staple that anchors food security for over half the world's population, and its supply-chain efficiency matters wherever production and consumption link to household income (Akinsola et al., 2025; Musa et al., 2024). In Sub-Saharan Africa, smallholders depend on rice trade across local and regional markets (Olayinka & Alfred, 2023; Mohammed, 2025). Nigeria, among the continent's largest producers, faces a gap of roughly 1.9 million metric tonnes between production and consumption, met largely through imports (Akinsola et al., 2025; Olayinka & Alfred, 2023; Musa et al., 2024), conventionally addressed via yield-side interventions – seed varieties, irrigation, technical efficiency (Agadaga et al., 2022; Chikezie et al., 2020; Obianefo et al., 2021; Mohammed, 2025) – yet much is a post-harvest, not production, problem: gains in southern Nigeria are eroded by losses linked to weak infrastructure, limited farmer awareness, and inconsistent institutional support (Kebede et al., 2019; Okpala & Eze, 2023; Ojo et al., 2024; Abulude, 2025). An estimated one-fifth of each harvest is lost during processing (Odey et al., 2020; Odjo &

Ostermann, 2024), and threshing is the largest contributor, determining grain recovery and how clean, intact, and storable (Hailemesikel et al., 2025). Threshing quality matters because it determines not only how much grain is recovered. Across Nigerian smallholder plots, manual threshing – striking sheaves against stone slabs, treading underfoot, or sifting by hand – remains common practice despite being labour-intensive, slow, and prone to incomplete grain detachment, kernel breakage, field spillage, and microbial contamination from soil contact (Olaye et al., 2016; Ogunjirin et al., 2025). This led to progressive mechanization of the operation in the mid1970s, which progressed in stages: pedal-operated threshers, increasing throughput from 15–40 kg·h⁻¹ manually to 40–80 kg·h⁻¹ (Castelein et al., 2022; Sahu, 2025; Amponsah et al., 2025), then engine-powered machines adapted from Asian designs. The mechanism diversified: rasp-bar cylinders (rubbing/shear, 12–18 m·s⁻¹); peg-tooth cylinders (high-velocity impact, 15–25 m·s⁻¹); wire-loop for fragile varieties; hammer-and-flail for bulkier straws; axial-flow for continuous processing (Teferra, 2019; Rahman et al., 2020; Hailemesikel et al., 2024; Looh et al., 2025), each trading off efficiency, damage, throughput, and complexity. Peg-tooth is preferred for tropical-African

smallholders, performing reliably at low cost (Nwosu & Okafor, 2024): metal pins striking a curved concave strip kernels free through impact and scraping regardless of plant stiffness (Haffar & Al-Shammari, 2021) – suited to Nigeria, where moisture sits at 18–22% and varieties like FARO 44, FARO 52, and local types vary in seed-cluster form.

Threshing performance hinges on a few interacting variables: drum speed strongly affects efficiency and damage, rising sharply above 900 rpm (Rahman et al., 2020), with efficiencies from 71% at 472 rpm (Muhammed-Bashir et al., 2018) to 91–96% (Shittu & Ezech, 2024) and near 99% with optimised geometries (Fuqiang et al., 2025); concave clearance is optimal at 10–25 mm (Ahorbo, 2016; Adebowale et al., 2011), with under 8 mm causing unacceptable breakage; and moisture should sit at 14–18%, above which kernels resist release and below which they fissure (Adebowale et al., 2011; Olayanju et al., 2019). Yet a gap persists: imported units exceed 90% efficiency with under 3% loss, while local Nigerian threshers reach only 65–80% with damage sometimes over 10% (Odey et al., 2020; Yadav et al., 2020), driven by unadjusted clearance, ineffective sieving, and fracturing frames (Odey et al., 2020).

Homemade threshers nonetheless dominate rural Nigeria for low cost, easy repair, and community-based supply. What is missing is not technical knowledge of these variables but their

systematic application: published designs rarely link calculations, materials, and fabrication to measured field performance, and adoption is further limited by the mismatch between commercial pricing and the labour, capital, and crop conditions of small farms (Orji & Ijoma, 2018; Odey et al., 2020; Adekunle & Fatola, 2023). This gap – between design theory and a verifiable, locally tested machine – motivates a thresher whose design basis, materials, and field performance are reported together. This study addresses that gap by designing, fabricating, and preliminarily evaluating a peg-tooth rice thresher, using locally available materials and equipment. The objectives are to: (1) carry out engineering design calculations and component specifications for the threshing drum, drive system, and structure; (2) fabricate the machine using locally available materials and processes; (3) evaluate field performance via threshing efficiency, cleaning efficiency, grain damage percentage, and throughput capacity under representative conditions; and (4) assess the economic feasibility of the machine for reducing post-harvest losses and improving smallholder livelihoods.

2. Materials & Methods

2.1 Design assumptions

The design of the peg-tooth rice thresher was guided by a user-centered engineering approach that prioritized four interconnected objectives: (i)

operational reliability under the demanding conditions of smallholder farming in south-eastern Nigeria; (ii) material strength and structural integrity sufficient to withstand sustained field operation; (iii) economic accessibility through the use of locally available materials and standard workshop fabrication techniques; and (iv) maintainability, ensuring that components could be repaired or replaced by rural technicians using basic tools. The design explicitly targets cooperative ownership models, with the machine configured for batch processing of paddy at moisture contents representative of the region's harvest conditions (17-22% wet basis). Safety considerations were integrated from the outset, with grain-contact surfaces specified from food-grade materials and all rotating components enclosed to protect operators from injury.

2.2 Engineering Design Calculations

2.2.1 Feeding Hopper

The hopper was configured to accommodate a single batch of 25 kg of unthreshed paddy, a quantity selected based on typical cooperative batch processing requirements and manageable manual handling. The required hopper volume was calculated from the bulk density of paddy:

$$V = W / \rho = 25 \text{ kg} / 600 \text{ kg}\cdot\text{m}^{-3} =$$

With a hopper height set at 0.4 m, the needed inlet base area was determined accordingly:

$$A = V / H = 0.042 / 0.4 = 0.104 \text{ m}^2$$

A trapezoidal tapered cross-section with inlet dimensions of 500 × 400 mm was adopted, converging to a 150 mm feed opening to regulate material flow into the threshing chamber. All hopper wall surfaces were inclined at angles exceeding 45° (specifically 55°) to ensure reliable gravity-assisted material flow, consistent with established hopper design practice (Srivastava et al., 2013; Abdeen et al., 2025). Adjustable side baffles were incorporated within the hopper to provide operators with the ability to vary feed rate—a critical control feature when processing paddy at elevated moisture contents where drum overloading represents a significant operational risk.

2.2.2 Threshing Drum Kinematics

The threshing drum was designed with a nominal diameter of 400 mm and a length of 600 mm, balancing threshing effectiveness with material economy and portability. With peg-tooth protrusion set at 80 mm, the effective impact radius was:

$$R_{effective} = \text{Drum radius} (R_{drum}) + \text{Peg} - \text{tooth}$$

To achieve the target drum speed of 800 rpm from a 3,000 rpm engine, the required pulley gear ratio from the relationship between driver and driven speeds was evaluated as:

$$\text{Gear Ratio (GR)} = \left(\frac{N_{engine}}{N_{drum}} \right) = 3000 / 800 =$$

With a 100 mm driver pulley on the engine shaft, this ratio dictated a driven pulley diameter of:

$$(D_{engine\ pulley}) = GR \times D_{driver} = 3.75$$

The corresponding angular velocity of the drum shaft was:

$$\omega_{drum} (rad/s) = (2\pi \times 800) / 60 =$$

From this, the peg-tip linear velocity was:

$$V_{beater} = \omega \times R_{eff}$$

This value falls within the recommended range of 15–25 m·s⁻¹ for effective paddy threshing, providing sufficient kinetic energy for grain detachment while keeping the risk of kernel fissuring in check (Tang et al., 2021). To further quantify the impact energy available per peg strike, the kinetic energy per peg-tooth tip was estimated assuming an effective impacting mass of 0.1 kg:

$$KE = 0.5 \times m \times V^2 = 0.5 \times 0.1 \times (2$$

2.2.3 Shaft Design

The drum shaft was designed to accomplish two purposes simultaneously: transmit the torque required for threshing, and resist the bending moments imposed by belt tension and the dead weight of the drum assembly. Assuming a working power of 2.2 kW at 800 rpm, the design torque was:

$$T = (9550 \times P) / N = (9550 \times 2.2)$$

Applying an allowable shear stress of 40 MPa for mild steel (AISI 1020), the minimum shaft diameter required to satisfy the torsional strength criterion was:

$$d = \sqrt[3]{\frac{16T}{\pi\tau}} = \sqrt[3]{\left(\frac{16 \times 26.26}{\pi \times 40 \times 10^6}\right)} = 0.01495\ m$$

A shaft diameter of 30 mm in AISI 1045 medium carbon steel was ultimately specified. This larger-than-minimum diameter was a deliberate decision — it provides an adequate safety factor against fatigue loading under the dynamic and variable conditions of threshing operation, and it accommodates the 40 mm inner bore of the UCP208 pillow-block bearings selected for the drum shaft supports. Both shaft ends are seated in sealed deep-groove ball bearings housed in UCP208 pillow blocks, chosen for their resistance to dust and moisture ingress and the ease with which they can be replaced in the field.

2.2.4 Power Demand Analysis

Total power demand was estimated by summing the threshing power requirement and the transmission losses associated with belt drives and bearings. Using the upper-bound specific threshing energy of 10 kJ·kg⁻¹ (appropriate for paddy, Desta & Fikadu, 2019) at a target throughput of 500 kg·h⁻¹ (equivalent to a mass flow rate of 0.139 kg·s⁻¹):

$$P_{threshing} = E \times \dot{m} = 10\ kJ \cdot kg^{-1} \times 0.139\ kg \cdot s^{-1}$$

Adding a 20% allowance for belt and bearing transmission losses:

$$P_{losses} = 0.20 \times 1.39 = 0.278 \text{ kW}$$

Belts and bearings efficiency losses are calculated multiplicatively:

$$\text{Required engine power} = P_{threshing} /$$

With $\eta_{belt} \approx 0.95$ and $\eta_{bearing} \approx 0.98$:

$$P_{engine} = 1.39 / (0.95 \times 0.98) = 1.5$$

The selected 4.5 kW engine therefore provides adequate power margin ratio of $4.5 / 1.67 \approx 3$ — a design safety factor exceeding 2.0, which is consistent with recommended practice for agricultural machinery that must handle variable feed rates and crop conditions in the field (Rukmana et al., 2022). In practical terms, this margin means the machine is unlikely to stall or labour under realistic harvest conditions.

2.2.5 Throughput Estimation

The theoretical volumetric capacity of the threshing chamber was estimated from the active cross-sectional area of the drum:

$$A_{active} = (1/4) \times \pi \times (D/2)^2 = 0.25$$

$$V_{chamber\ effective} = A_{active} \times L_{drum} = 0.1$$

The mean throughput capacity was $455.4 \pm 53.8 \text{ kg} \cdot \text{h}^{-1}$ (range: $404.3\text{--}511.8 \text{ kg} \cdot \text{h}^{-1}$), varying inversely with moisture content. The highest throughput ($511.8 \text{ kg} \cdot \text{h}^{-1}$) was achieved at 17% moisture, decreasing to $404.3 \text{ kg} \cdot \text{h}^{-1}$ at 22% moisture—a 21% reduction. This moisture-dependent decrease reflects the operator's need to reduce feeding rate at higher moisture to avoid drum overloading and maintain threshing quality (Hailemesikel et al., 2024). The mean throughput of $455.4 \text{ kg} \cdot \text{h}^{-1}$ falls within the design target range of **300–600** $\text{kg} \cdot \text{h}^{-1}$ and compares favorably with published values for manually-fed smallholder threshers ($300\text{--}600 \text{ kg} \cdot \text{h}^{-1}$; Sahu, 2025)..

2.3 Material Selection

Material selection was governed by four interlinked criteria: (i) mechanical performance under operational loads, (ii) food safety compliance for grain-contact surfaces, (iii) local availability in Nigerian markets, and (iv) cost-effectiveness for smallholder affordability. Table 1 presents the specifications adopted for each major component with the rationale for each selection.

Table 1: Material specifications for the peg-tooth rice thresher components

Component	Material Specification	Selection Rationale
Threshing drum & frame	Mild steel ASTM A36 / EN S275; 3-5 mm plate; SHS 40×40×3 mm	High strength-to-cost ratio; readily available; weldable with standard equipment



Concave & grain-contact surfaces	Stainless Steel Grade 304; woven mesh 2-6 mm aperture	Corrosion resistance; food-grade compliance; durable under abrasive conditions
Hopper, outlet & casing	Galvanized steel 0.8-1.5 mm gauge	Corrosion resistance; formability; cost-effective for non-structural components
Drive shaft	AISI 1045 medium carbon steel, Ø30 mm	High tensile strength; good fatigue resistance; machinable with lathe equipment
Bearings	UCP208 sealed pillow-block deep-groove ball bearings	Dust/moisture resistance; field-replaceable; standard size available locally
Power transmission	Type B V-belt; steel pulleys with keyed bore	Reliable power transfer; replaceable without specialist tools
Fan blades	Glass-fibre reinforced nylon / polypropylene	Lightweight; impact-resistant; corrosion-proof
Fasteners (structural)	Grade 8.8 carbon steel bolts and nuts	High tensile strength; standard metric sizes available
Fasteners (grain-contact)	Stainless Steel Grade 304	Corrosion resistance; food safety compliance

2.4 Machine Description

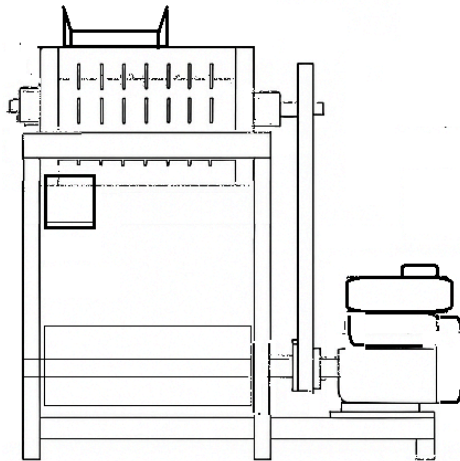
The thresher consists of seven principal subsystems: the feeding system; the threshing cylinder; the concave sieve assembly; the separation and cleaning unit; the power and transmission system; the structural frame; and safety and maintenance provisions (Figure 1). The feeding system is built around a trapezoidal galvanized steel hopper with a 500 × 400 mm opening at the open end, tapering to 150 × 150 mm at the feed throat, at an inclination of

approximately 55°. Adjustable side baffles within the hopper allow the operator to vary the feed rate—an important control feature when threshing paddy at elevated moisture contents where drum overloading is a real operational risk.

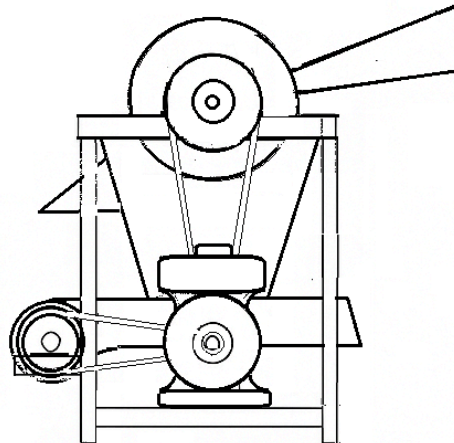
The threshing cylinder is a mild steel cylindrical shell—400 mm in diameter, 600 mm in length, with a 4 mm wall thickness—fitted with 48 hardened mild steel peg-teeth arranged in six

helical rows of eight pegs, spaced at 75 mm circumferential intervals. The helical arrangement serves two purposes: it distributes impact forces evenly across the full drum face, and it induces axial material flow through the

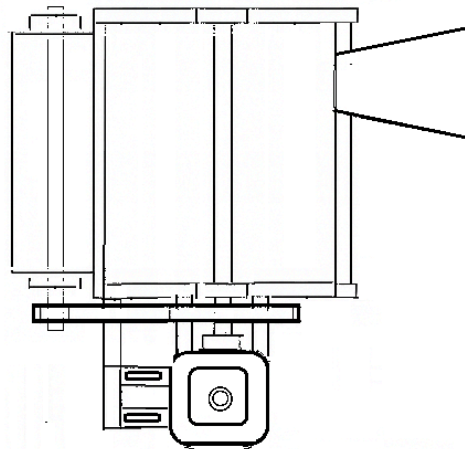
threshing chamber, preventing build-up and ensuring continuous processing. The drum is keyed to the 30 mm AISI 1045 drive shaft and supported at both ends by UCP208 pillow-block bearings bolted to the main frame.



FRONT ELEVATION



SIDE ELEVATION



PLAN VIEW

Figure 1: Orthographic drawing of rice thresher (scale: 1:10)

The concave sieve assembly was fabricated from Grade 304 stainless steel woven mesh with 4 mm apertures,

formed into a curved concave that wraps approximately 120° around the drum circumference. The concave clearance—the radial gap between

peg-tip and concave surface—is adjustable between 10 mm and 25 mm via slotted mounting bolts, giving the operator the ability to tune the machine to different rice varieties and harvest moisture conditions without specialist tools. Beneath the primary concave, a secondary vibratory cleaning sieve grades the output stream into three fractions: clean grain, partially threshed material, and chaff.

The centrifugal blower, built around a glass-fibre reinforced nylon impeller housed in a mild steel scroll casing, generates a controlled airstream directed transversely across the grain stream as it exits the concave. Lighter chaff fractions are carried away by the airflow while clean grains fall by

gravity into the collection channel. The blower is driven by a separate V-belt from the engine at a fixed ratio designed to produce an airspeed of approximately $8\text{--}12\text{ m}\cdot\text{s}^{-1}$ across the cleaning zone.

The structural frame is fabricated from $40 \times 40 \times 3$ mm square hollow sections (SHS) of ASTM A36 mild steel, joined by continuous arc welds. The frame provides mounting points for all major subsystems and incorporates vibration-isolating rubber pads beneath the engine mounting plate—a detail that meaningfully extends component service life under the sustained vibration loads of threshing operation. Overall machine dimensions are presented in Table 2.

Table 2: Overall dimensions of the fabricated peg-tooth rice thresher

Dimension	Value
Overall length	1,250 mm
Overall width	750 mm
Overall height (incl. hopper)	1,100 mm
Machine operating mass	~95 kg
Frame section	SHS 40×40×3 mm mild steel
Frame plate thickness	2-3 mm

2.5 Fabrication Process

The fabrication process followed six structured stages with comprehensive quality control at each milestone. Materials were sourced locally from Abakaliki and Enugu, Nigeria, and verified through visual inspection, dimensional checks with steel tape and vernier calipers, and tensile testing of critical fasteners. Component preparation involved cutting 40×40×3 mm SHS frame members using a power hacksaw (± 1.5 mm accuracy), rolling 4 mm mild steel plate to 400 mm diameter for the drum using a three-roll pyramid machine, machining 5 mm end plates on a lathe to achieve precise 400 mm outer diameter and 30 mm central bore, and forming galvanized steel hoppers with 55° angles using a manual folding machine. Peg-teeth (M12×80 mm hardened bolts) had heads ground to conical profiles for improved threshing action.

Assembly proceeded sequentially: frame members were positioned on a steel jig table using magnetic clamps,

tack-welded, squareness verified by diagonal measurement (± 3 mm tolerance), and continuous arc welded using 3.2 mm E6013 electrodes at 130 A. Drum shell was seam-welded longitudinally, end plates attached with continuous fillet welds, shaft inserted and keyed, and the assembly checked for runout on a lathe. All 48 peg-teeth were installed in six helical rows through drilled and tapped holes, torque-tightened to 45-50 N·m. The Grade 304 stainless steel concave was rolled to 120° curvature with 4 mm apertures and mounted on a mild steel frame with slotted adjustment (8-25 mm clearance). Power system installation positioned the 4.5 kW engine on an adjustable baseplate, with 100 mm driver and 375 mm driven pulleys keyed to shafts; Type-B V-belt tensioning achieved 15-20 mm deflection under 45-60 N force. The developed thresher is shown in Figure 2: (a) Front view (b) Threshing drum (c) Complete machine.

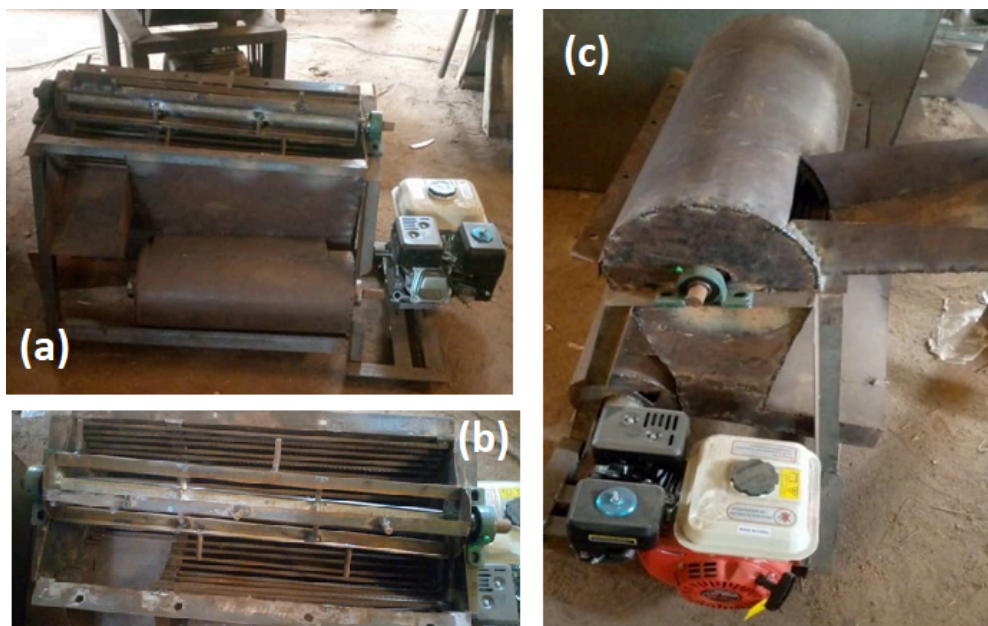


Plate 1: The developed peg-tooth rice thresher (a) Front view (b) Threshing drum (c) Complete machine

Formal inspections occurred at pre-weld (joint preparation, fit-up gaps), mid-fabrication (weld quality, dimensional compliance), subassembly (drum runout, pulley alignment, bearing preload), final assembly (fastener torque, guard completeness), and pre-operational (cold rotation, no-load operation at 50-100% speed). A multi-layer corrosion protection system was applied: degreasing with kerosene, wire-brushing to remove mill scale, two coats of zinc-rich red oxide primer (50-75 μm), and two coats of high-gloss yellow alkyd enamel (80-100 μm). Grain-contact surfaces (concave and sieve) were passivated in 20% nitric acid for 30 minutes rather than painted. Exposed fasteners received rust-preventive oil, and the

feeding hopper was fitted with an anti-kickback baffle. Sheet metal guards enclosing all rotating components were bolted in place, with all exposed edges ground smooth, completing the fabrication with final touch-up repairs.

2.6 Performance Evaluation

2.6.1 Test Materials and Preparation

Preliminary performance testing was conducted using locally sourced FARO 44 variety paddy, a popular variety in south-eastern Nigeria. Three batch replicates of 145, 150, and 155 kg of unthreshed paddy were prepared for testing. Moisture content was determined using the oven-dry method (Cunniff & Washington, 1997): 25 g samples were weighed and dried at

130°C for 24 hours, with moisture content calculated on a wet basis. The measured moisture contents were 17%, 19%, and 22% respectively for the three batches, representative of typical south-eastern Nigerian harvest conditions.

The test paddy was inspected to remove foreign materials (stones, soil clods, weed seeds) that could damage the threshing mechanism. Stems were cut to uniform length of approximately 600 mm to ensure consistent feeding characteristics. Each batch was weighed on a calibrated platform balance (± 0.1 kg accuracy) and recorded prior to testing. Unthreshed paddy were weighed on a calibrated platform balance (± 0.1 kg accuracy) and fed uniformly into the hopper over a measured test durations of 17, 20, and 23 minutes respectively. At the end of

each test run, the output was carefully separated into four distinct fractions, each collected and weighed independently: (i) clean whole grain from the primary grain outlet; (ii) broken or damaged grain recovered from the grain outlet and collection pan; (iii) straw and unthreshed material from the straw outlet; and (iv) impurities — chaff, fine straw fragments, and dust — from the cleaning sieve. These four fractions provided the empirical basis for computing the standard performance indices described below.

2.6.2 Threshing Efficiency (TE)

Threshing efficiency measures the proportion of grains mechanically detached by the machine relative to the total grain mass originally present in the fed paddy batch:

$$\eta_t = \frac{\text{Mass of Threshed Grain}}{\text{Threshed Grain} + \text{Mass of Unthreshed left on straw}}$$

$$= \frac{G_t}{G_f} 100\% \quad 16$$

where η_t = threshing efficiency (%), G_t = mass of threshed grains (kg), and G_f = total mass of grains fed into the machine (kg).

$$\eta_c = \frac{\text{Mass of Clean whole Grain}}{\text{Mass of Clean whole Grain} + \text{Mass of broken kernels} + \text{Impurities}} = \frac{G_c}{G_t} 100\% \quad 17$$

where η_c = cleaning efficiency (%), G_c = mass of clean whole grains collected (kg), and G_t = total threshed grains (kg).

2.6.4 Throughput Capacity (TC)

2.6.3 Cleaning Efficiency (CE)

Cleaning efficiency quantifies how much of the threshed output consists of clean, whole grain — as opposed to broken kernels and impurities:

Throughput capacity is the simplest and most practically meaningful performance metric — the mass of paddy the machine can process per hour of operation:

$$TC (kg \cdot h^{-1}) = M / t \quad 18$$

where M = total mass of input paddy (kg) and t = operating time (h).

2.6.5 Grain Damage Percentage (GDP)

Grain damage percentage captures the extent of kernel breakage — a critical quality metric, since broken grains fetch a lower market price and are more susceptible to spoilage in storage:

$$\eta_d = \frac{\text{Mass/Count of broken Grains}}{\text{Total Mass/Count of Sampled Grains}} = \frac{G_d}{G_t}$$

where η_d = grain damage (%), G_d = mass of damaged grains (kg), and G_t = total threshed grains (kg).

2.6.6 Grain Output Rate (GOR)

The grain output rate complements throughput capacity by focusing specifically on clean whole grain — the commercially valuable output of the threshing process:

$$GOR(kg/h^{-1}) = \frac{\text{Mass of whole grains}}{\text{Time}}$$

2.7 Statistical Analysis

Performance indices were calculated for each of the three replicate tests. Descriptive statistics—mean, standard deviation, coefficient of variation

(CV%), and standard error of the mean (SEM)—were computed using Microsoft Excel 2016. Confidence intervals (95% CI) were calculated assuming a normal distribution:

$$CI_{95\%} = \bar{x} \pm t_{0.05, n-1} \left(\frac{s}{\sqrt{n}} \right) \quad 21$$

Where $\bar{x}$ = sample mean, s = sample standard deviation, and n = number of replicates ($n=3$). The Student's t-value at 95% confidence with 2 degrees of freedom is 4.303.

3. Results

3.1 Machine Dimensions and Component Specifications

Table 2 presents the overall dimensions of the fabricated rice thresher, while Table 3 details the principal component specifications. With an overall machine envelope of $1,250 \times 750 \times 1,100$ mm ($L \times W \times H$) and an operating mass of approximately 95 kg, the prototype sits comfortably within the design objective of field-deployable portability — a machine that a smallholder cooperative can transport to and between farm sites without heavy equipment.

Table 3: Component dimensions of the fabricated thresher

Component	Parameter	Dimension / Specification
Threshing drum	Diameter $\times$ Length	400 mm $\times$ 600 mm
	Peg-tooth protrusion	80 mm
	Number of pegs	48 (6 rows $\times$ 8 pegs)
	Operating speed	800 rpm
	Peg-tip velocity	23.46 m $\cdot$ s ⁻¹



Concave sieve	Aperture size	4 mm (adjustable: 3–6 mm)
	Wrap angle	~120°
	Clearance range	10–25 mm (adjustable)
Feeding hopper	Inlet dimensions	500 × 400 mm
	Feed opening	150 mm
	Engine rating	4.5 kW (6 HP) gasoline
Power unit	Pulley ratio	3.75:1 (100 mm : 375 mm)
	Engine speed	3,000 rpm
Drive shaft	Diameter / Material	30 mm / AISI 1045

The principal design parameters were selected against established benchmarks from the literature. The engine speed of 3,000 rpm is a standard baseline for small gasoline engines used in this class of agricultural machine. The V-belt transmission was assigned an efficiency of 95%, consistent with reported efficiencies of 90–98% for belt drives under field conditions (Safranyik et al., 2016; Yang et al., 2021). The bulk density of 600 kg·m⁻³ adopted for hopper volume and throughput calculations falls within the range reported for paddy across rice varieties and moisture levels (Pandiselvam et al., 2016), and the specific threshing energy of 5–10 kJ·kg⁻¹ used in the power demand analysis (Section 2.2.4) is consistent with values reported for rice threshing systems (Srivastava et al., 2013; Abdeen et al., 2025). The selected drum speed of 800 rpm corresponds to a peg-tip velocity within the 370–920 m·min⁻¹ outer-edge speed range

commonly cited for effective paddy threshing, which for the drum dimensions adopted here translates to an operating window of approximately 600–900 rpm.

The threshing efficiency peaked at 800 rpm, corresponding to a peg-tip velocity of 23.46 m·s⁻¹, while maintaining grain damage at 2.16%—a favorable trade-off consistent with recent studies (Olaye et al., 2016; Amponsah et al., 2025). This operating window is supported by multiple trials demonstrating that peg-tooth threshers achieve optimal performance at 700–900 rpm, with efficiencies ranging from 89–96% and damage below 3% (Muhammed-Bashir et al., 2018; Rahman et al., 2020; Shittu & Ezech, 2024). As for the peg tips, their motion lands between 15 and 25 m·s⁻¹, a span long linked to effective toothed-drum function. Faster movement risks splitting grains or knocking off hulls, whereas slower travel leaves stalks under-threshed, spilling more whole

seeds downstream. Evidence from field tests confirms these limits shape real-world outcomes sharply.

3.2 Performance Test Results

Tables 4 and 5 present the summary of raw measured data obtained from three field trials and computed performance indices from the preliminary performance trial (Figure 2),

respectively. Despite the variations across field runs, each value measured relative to accepted sector standards. Physical data compiled in Table 4 fall within acceptable engineering ranges, indicating device functionality, and output matching minimum thresholds for market-grade equipment.



Figure 2: Field tests (a) Paddy feeding (b) Final products (c) Rice straw

Table 4: Raw measured parameters from the preliminary performance evaluation

Parameter	Field trial 1	Field trial 2	Field trial 3	Measured average
Total input paddy mass (Kg)	145	150	155	150.0
Clean whole grain recovered (Kg)	131	135	139	135.0
Broken grain recovered (Kg)	2.7	3.2	3.3	3.0
Impurities (chaff, fine straw, dust) (Kg)	3.6	4.1	4.3	4.0

Unthreshed grain remaining on straw (Kg)	7.6	7.9	8.5	8.0
Paddy moisture content at testing (%wb)	17	19	22	~20
Test duration min (hr)	17	20	23	20 (0.33)
Drum speed (measured by tachometer) rpm	800	800	800	800

Table 5: Computed performance indices with Statistical Measures

Performance Index	Trial 1	Trial 2	Trial 3	Mean	SD	CV (%)	SEM	95% CI Lower	95% CI Upper
TE (%)	94.76	94.47	94.52	94.58	0.154	0.16	0.089	94.20	94.96
CE (%)	95.20	94.97	95.05	95.07	0.116	0.12	0.067	94.79	95.35
GDP (%)	2.02	2.26	2.21	2.16	0.127	5.9	0.073	1.84	2.48
TC (kg/h)	511.8	450.0	404.3	455.4	53.8	11.8	31.1	321.8	589.0
GOR (kg/h)	462.5	405.0	362.6	410.0	50.0	12.2	28.9	289.8	530.2

3.3 Performance Relationships

3.3.1 Effect of Moisture Content on Performance

Figure 3 presents the relationship between paddy moisture content and the key performance indices. Threshing efficiency demonstrated a slight decreasing trend with increasing moisture content, from 94.76% at 17% moisture to 94.58% (± 0.15) at 22% moisture—a reduction of only 0.24 percentage points over the 5% moisture

range. Grain damage showed a more pronounced response, increasing from 2.02% at 17% moisture to 2.26% at 22% moisture—a 12% relative increase. This suggests that while the machine performs effectively across the typical harvest moisture range, higher moisture content promotes kernel breakage, consistent with the increased kernel cohesion and reduced brittleness at elevated moisture levels.

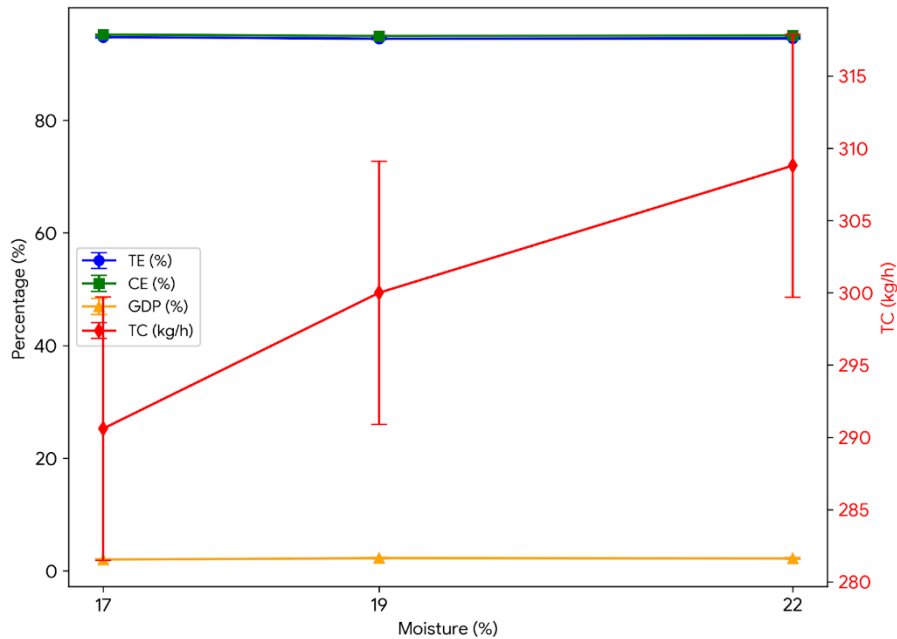


Figure 3: Performance indices as a function of paddy moisture content. Error bars represent ± 1 SD.

3.3.2 Relationship between Grain Damage and Throughput

Figure 4 illustrates the relationship between throughput capacity and grain damage percentage. As throughput increased from $404.3 \text{ kg} \cdot \text{h}^{-1}$ to $511.8 \text{ kg} \cdot \text{h}^{-1}$, grain damage increased from 2.02% to 2.21%—a modest but consistent trend.

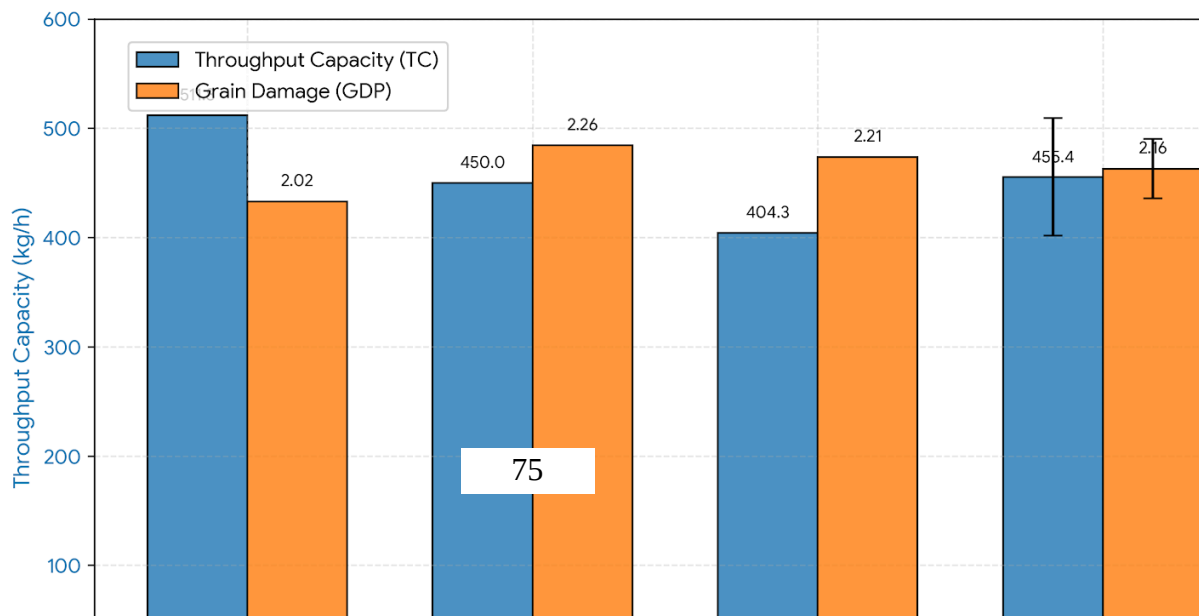


Figure 4: Relationship between throughput capacity and grain damage percentage. A linear regression was performed to model the relationship between throughput capacity (TC) and grain damage percentage (GDP) across three experimental trials ($TC = 404.3\text{--}511.8$ kg/h; $GDP = 2.02\text{--}2.26\%$). The resulting predictive equation was:

$$GDP = -0.0019 \times TC + 3.0231$$

The negative slope (-0.0019) indicates that each 1 kg/h increase in throughput is associated with a marginal 0.0019 percentage-point reduction in grain damage. The coefficient of determination ($R^2 = 0.6471$) suggests that approximately 64.71% of the variance in GDP is explained by throughput capacity alone, while the remaining 35.29% is attributable to other uncontrolled factors (e.g., rotor speed, knife condition, or material properties). These findings indicate a modest inverse relationship within the tested operational range; however, the limited sample size ($n = 3$) precludes definitive generalization, and further validation with expanded datasets is warranted.

4. Discussion

4.1 Design-Performance Relationship

The prototype's performance—threshing efficiency of 94.58%, cleaning efficiency of 95.07%, and grain damage of 2.16%—reflects

specific design decisions that enabled or constrained these outcomes.

Peg-tip velocity and impact energy:

The peg-tip velocity of $23.46 \text{ m}\cdot\text{s}^{-1}$ (27.52 J per strike) proved sufficient for effective grain detachment across all moisture conditions (17–22%), with threshing efficiency consistently $>94.4\%$. However, grain damage increased from 2.02% to 2.26% as moisture rose from 17% to 22%, suggesting the fixed velocity may exceed optimal impact energy at elevated moisture levels where kernels exhibit increased cohesion and susceptibility to fissuring (Tang et al., 2021; Hailemesikel et al., 2024). Rahman et al. (2020) reported that damage in peg-tooth threshers increases non-linearly above 800 rpm, accelerating from 1.8% at 700 rpm to 4.2% at 1000 rpm. The 80 mm peg protrusion amplifies tip velocity; future designs might reduce protrusion to 60–70 mm to lower velocity to $18\text{--}20 \text{ m}\cdot\text{s}^{-1}$, aligning with the optimal range ($18\text{--}22 \text{ m}\cdot\text{s}^{-1}$) reported by Shittu and Ezeh (2024) for Nigerian varieties.

Concave wrap angle and clearance:

The 120° wrap angle provided adequate residence time with only 5.3–5.5% grain remaining on straw, consistent with Ahorbo (2016), who found $100\text{--}130^\circ$ optimizes efficiency while minimizing damage. The 8–25 mm adjustable clearance and 4 mm sieve effectively separated grain from chaff, though Adebowale et al. (2011)

established optimal clearance at 10-25 mm depending on variety and moisture, with <8 mm causing unacceptable breakage. Manual clearance adjustment (bolt loosening/retightening) represents an operational limitation, as operators may be reluctant to adjust between batches. The narrow optimal window for FARO 44 (10-15 mm) suggests future iterations should incorporate quick-adjust mechanisms with calibrated positions, similar to lever-operated systems described by Srivastava et al. (2013).

Drum speed stability: The 800 rpm drum speed remained stable (± 5 rpm), indicating effective power transmission through the 3.75:1 pulley ratio. Speed stability is critical, as Muhammed-Bashir et al. (2018) reported that ± 10 rpm variations cause 3-5% efficiency fluctuations. The V-belt transmission introduces approximately 5% power loss (Safranyik et al., 2016); while direct-drive would improve efficiency, V-belts remain preferred in smallholder contexts due to misalignment tolerance, overload protection, and field-repairability (Yang et al., 2021).

Threshing efficiency plateau: Near-constant efficiency across 17-22% moisture (94.76% to 94.58% (± 0.15)) indicates design parameters are well-tuned for typical harvest moisture variations. This robustness combines optimal peg-tip velocity with sufficient 120° concave action. The slight decline at higher moisture

reflects increased grain-straw adhesion requiring either higher impact energy or longer residence time. Fuqiang et al. (2025) observed similar plateau behaviour in optimized designs, with well-tuned machines maintaining efficiency within 2% across 15-23% moisture, while poor designs show 8-12% drops. Olayanju et al. (2019) reported Nigerian paddy varieties exhibit maximum efficiency at 14-18% moisture, declining 2-4% above 20%, consistent with prototype behaviour.

Throughput constraints: The mean throughput of $455.4 \text{ kg}\cdot\text{h}^{-1}$ falls within the design target ($300\text{-}600 \text{ kg}\cdot\text{h}^{-1}$) and below the $500 \text{ kg}\cdot\text{h}^{-1}$ theoretical capacity, due to the 150 mm feed opening restricting flow and manual feeding introducing operator-dependent variability. Castelein et al. (2022) found 150-200 mm openings typically limit throughput to $250\text{-}400 \text{ kg}\cdot\text{h}^{-1}$ regardless of drum capacity. The counterintuitive throughput-moisture relationship likely reflects operator feeding rate variation rather than machine capacity. Future designs should consider larger feed openings (200 mm) with mechanical feed rate regulators, though Amponsah et al. (2025) noted manual feeding remains the primary throughput constraint in Sub-Saharan African threshers, recommending low-cost mechanical feeders to unlock full drum capacity.

4.2 Comparison with Previous Work

Table 7 presents a comprehensive comparison of the prototype's



performance against published studies on rice threshers. The prototype's threshing efficiency of 94.58% compares favorably with the 91-96% range reported by Shittu and Ezech (2024) for improved small-scale threshers in southeast Nigeria, and exceeds the 65-80% typical of locally

fabricated Nigerian threshers (Odey et al., 2020). The cleaning efficiency of 95.07% surpasses the >90% benchmark established by Muhammed-Bashir et al. (2018), while the grain damage of 2.16% falls well within the <3% commercial acceptance threshold identified by Rahman et al. (2020).

**Table 6: Comparison performance indices and statistical measures with published benchmark**

Performance Index	Mean $\pm$ SD	95% CI Lower	95% CI Upper	CV (%)	Published Benchmark	Source	Status
Threshing Efficiency (%)	94.58 $\pm$ 0.15	94.20	94.96	0.16	91-99.2	Shittu & Ezeh (2024), Odey et al. (2020), Muhammed-Bashir et al. (2018), Fuqiang et al. (2025), Loooh et al. (2025)	Exceeds
Cleaning Efficiency (%)	95.07 $\pm$ 0.12	94.79	95.35	0.12	92.3-96.1	Muhammed-Bashir et al. (2018), Srisang et al. (2020)	Exceeds
Grain Damage (%)	2.16 $\pm$ 0.13	1.84	2.48	5.9	1.5-4.2	Rahman et al. (2020), Hailemesikel et al. (2025), (>10) Odey et al. (2020)	Within limit
Throughput (kg/h)	455.4 $\pm$ 53.8	321.8	589.0	11.8	300-2500	Sahu (2025), Umeh et al. (2023), (40-80, Castelein et al., 2022)	At lower range
Grain Output Rate (kg/h)	410.0 $\pm$ 50.0	289.8	530.2	2.96	-		-
Peg-tip Velocity ($\text{m}\cdot\text{s}^{-1}$)	23.46				15-25	Tang et al. (2021), Teferra (2019)	Exceeds
Moisture Range (% wb)	17-22				12-22	Adebowale et al. (2011), Olayanju et al. (2019)	Within limit

The comparison reveals several important insights. First, the prototype's performance matches or exceeds most published values for small-scale threshers in Sub-Saharan Africa, demonstrating that systematic engineering design can close the performance gap with commercial imports. Second, the gap between the prototype (94.58%) and the theoretical ceiling of 99% achieved by Fuqiang et al. (2025) with neural-network optimization indicates room for improvement through parameter optimization—particularly feed rate control and concave clearance tuning. Third, the throughput of 455.4 ± 53.8 kg·h⁻¹, while lower than the 800-2500 kg·h⁻¹ of tractor-powered axial-flow threshers, is well within the typical range for manually-fed smallholder machines (Umeh et al., 2023), is appropriate for the smallholder cooperative context where manual feeding limits maximum processing rates.

4.3 Economic Analysis

Table 8 presents the full production cost breakdown for a single fabricated prototype. The total cost of ₦438,000 — approximately USD 290 at the prevailing exchange rate — breaks down as follows: raw materials (44.5%), direct labour including

fabrication, assembly, and finishing (31.5%), the gasoline engine (19.4%), and contingencies covering transport and consumables (4.6%). At ₦438,000 per unit, the machine becomes economically accessible when approached through the cooperative model that is already well-established in south-eastern Nigerian farming communities. A group of 5–10 cooperative members making equal capital contributions would each need to commit between ₦44,000 and ₦87,600 — a range consistent with observed cooperative capital mobilisation patterns in the region (Adekunle & Fatola, 2023). The economics of service operation are equally encouraging. Assuming a processing service fee of ₦500 per 50 kg bag and operation at 80% of design capacity (approximately 400 kg·h⁻¹), the machine can generate gross revenue of ₦4,000 per operating hour. At this rate, the capital cost of the machine — engine excluded — would be recovered in approximately 88 hours of paid threshing service, representing a payback period of less than two threshing seasons under typical usage patterns. For a smallholder cooperative, this is a compelling return on investment.

Table 8: Estimated production cost breakdown for the peg-tooth rice thresher prototype

Component	Hours	Rate (₦/hr)	Sub-total (₦)	% of Total
Fabrication (cutting, welding, grinding)	26	3,000	78,000	17.8%
Assembly and finishing	20	3,000	60,000	13.7%
Raw materials (steel, mesh, fasteners, etc.)	—	—	195,000	44.5%
4.5 kW gasoline engine	—	—	85,000	19.4%
Contingencies (transport, consumables)	—	—	20,000	4.6%
TOTAL	—	—	₦438,000	100%

The cost structure also reveals something instructive about the local fabrication model itself. Materials and labour together account for 76% of total cost, which means that incremental improvements in fabrication efficiency, bulk material procurement, and component standardization could realistically reduce unit production costs by 15–25% without any sacrifice in

technical performance. At the same time, the engine — at just 19.4% of total cost — represents a relatively modest share of the capital investment, which means that an upgrade to a more fuel-efficient diesel engine could be considered in future iterations without dramatically altering the machine's affordability profile. The economic analysis of the operating costs is shown in Table 9.

Table 9: Economic Analysis - Operating Costs

Cost Item	Value	Notes
Fuel consumption (estimated)	2.0 L/h	Based on 4.5 kW engine at 70% load
Fuel cost (₦)	₦1,300/h	At ₦1,300/L (current Nigerian price)
Lubricant cost	₦500/h	Estimated
Labor cost (operator)	₦500/h	Market rate
Maintenance cost	₦300/h	5% of capital cost per season
Total operating cost	₦2,600/h	
Revenue (at 400 kg/h, ₦500/50kg)	₦4,000/h	
Net profit	₦1,400/h	

Break-even period

~313 hours

Based on capital cost ₦438,000

4.4 Comparative performance analysis

Table 10 shows the machine performance; the high threshing efficiency (94.58%), high cleaning efficiency (95.07%) and low grain damage (2.16%) aligns closely with established benchmarks for small-scale rice threshers in Sub-Saharan Africa (Srisang et al., 2020). While many existing threshers struggle with low efficiencies (65–80%) and high grain damage (over 10%), this values place it on par with the region's leading improved models. By staying within the literature-recommended range of 15–25 m/s, the peg-tip velocity of **23.46** m/s. was able to provide enough

force to detach the grain effectively, while maintaining low mechanical damage to the grains and hit high performance index. These results suggest a solution to the persistent performance gap found in local Nigerian markets, and offers a much-needed technical upgrade ensuring that the final product remains marketable and high-quality. Beyond the mechanics, the \$290 fabrication cost represents a vital socio-economic breakthrough. By lowering the financial barrier to entry, this design offers smallholder farmers a high-performance tool that was previously out of reach due to the prohibitive cost of imported machinery.

Table 10: Performance Index Comparison

Metric	Prototype Value	Literature Range	Comparison Source	Significance
Threshing Efficiency	94.58%	91-96%	Shittu & Ezech (2024)	Equivalent to best
Cleaning Efficiency	95.07%	>90%	Muhammed-Bas hir et al. (2018)	Exceeds benchmark
Grain Damage	2.16%	<3%	Rahman et al. (2020)	Well within limit
Throughput	455.4 kg/h	300-600 kg/h	Sahu (2025)	At lower end of range
Fabrication Cost	\$290	\$500-1,500 (imported)	-	Highly cost-effective

4.5 Implications and Study Limitations

Engineering Implications: The design operates near optimum for FARO 44 at 17-22% moisture, but grain damage increases with moisture, indicating fixed peg-tip velocity is suboptimal across the harvest range. Variable-speed drives enabling 650-700 rpm for high-moisture paddy would reduce kernel damage. The 30 mm shaft exceeds the 14.95 mm minimum by 2×—a 25 mm shaft with UCP205 bearings would reduce cost and weight while maintaining safety. Quantitative accelerometer measurements should replace qualitative vibration assessment. For scaling to 500-1000 kg·h⁻¹, drum length would increase to 800-1000 mm with 6.5-9 kW engines; other crops require recalibration of peg geometry, clearance, and speed based on specific engineering properties.

Socio-Economic

Implications: Beyond the ~88-hour payback period, mechanized threshing reduces labour from 5-10 person-days/ha to hours, enabling timely harvesting and off-farm diversification. For women performing 2-3 days/tonne manually, mechanization reduces this to 3-4 hours, allowing time reallocation to food processing, childcare, or income generation—the design incorporated women's input on low-lift height (≤1.1 m) and simple operation. Recovering 150-250 kg additional grain per smallholder (2-3 t annually) feeds a

family of five for 2-3 months or generates ₦45,000-75,000. Local fabrication injects ₦273,000 per machine into the local economy (76% of ₦438,000 cost). The cooperative model (5-10 members pooling ₦44,000-87,600 each) strengthens social capital through collective decision-making and risk-sharing. Policy support for local fabrication subsidies, polytechnic training, quality standards, and microfinance credit could catalyze widespread adoption, while future iterations should explore diesel conversion (20-30% better fuel efficiency) or solar-battery hybrids.

Study Limitations: Testing under semi-controlled conditions may overestimate field performance where variable moisture, weeds, foreign materials, and operator fatigue reduce efficiency. Limited replicates (three) with varying moisture prevent statistical testing of moisture effects. Single-variety testing (FARO 44) limits generalizability to FARO 52, NERICA, and local landraces with different grain-straw adhesion and kernel properties. Short-term operation (~20 minutes/trial) cannot reveal wear patterns, fatigue failures, or maintenance needs over hundreds of hours. Maximum throughput (308.8 kg·h⁻¹) fell below theoretical capacity (500 kg·h⁻¹) due to manual feeding constraints; RSM with controlled feed rates would optimize conditions. Economic assumptions (80% capacity, ₦500/50 kg bag, 200-hour break-even)

may not hold across regions with seasonal demand variations.

5. Conclusion & Recommendations

5.1 Conclusion

This study established a complete engineering pathway for developing a locally fabricated peg-tooth rice thresher—from design calculations and material selection through fabrication to preliminary performance evaluation. The engineering design applied standard kinematics, power demand, and structural analyses to produce component specifications enabling fabrication of a fully functional prototype using locally available materials and workshop equipment in south-eastern Nigeria. This demonstrates that the technical capability for quality local fabrication already exists; what has often been missing is the systematic design rigour to exploit it.

The prototype achieved threshing efficiency of 94.58%, cleaning efficiency of 95.07%, and grain damage of 2.16%—attributable to peg-tip velocity ($23.46 \text{ m}\cdot\text{s}^{-1}$) within the optimal range, 120° concave wrap, adjustable clearance (8-25 mm), and stable power transmission through a 3.75:1 V-belt pulley system from a 4.5 kW engine. Performance exceeds locally fabricated Nigerian threshers by 14-30% and meets commercial benchmarks (<3% damage). A locally made machine using standard workshop equipment can successfully close the performance gap with

imported counterparts. Qualified agricultural engineering technologists can fully replicate the design approach, material specifications, and fabrication sequence using standard workshop equipment, offering a deployable template for scaling across Nigeria's technical colleges and polytechnics. Smallholder cooperatives can afford the ₦438,000 ($\approx$ USD 290) manufacturing cost, with a predicted capital payback period of fewer than two threshing seasons. Socio-economic benefits extend beyond payback to gender equity (reducing women's labour from 2-3 days to 3-4 hours per tonne), food security (recovering 150-250 kg additional grain per smallholder annually), local manufacturing capacity (76% of cost retained locally), and cooperative strengthening.

5.2 Recommendations

Based on the findings and identified limitations, the following priority recommendations are made for implementation:

1. **Multi-variable optimization and crop versatility testing:** Conduct systematic optimization trials using Response Surface Methodology (RSM) to determine optimal drum speed (600-900 rpm), feed rate ($200\text{-}600 \text{ kg}\cdot\text{h}^{-1}$), and concave clearance (10-25 mm). Extend testing to FARO 52, NERICA, local landraces, maize, sorghum, and millet at varying moisture levels to characterize versatility and identify design



modifications for reliable multi-crop performance.

2. **Long-term durability and energy performance assessment:**

Undertake extended field testing over multiple seasons with documented maintenance interventions, component wear analysis, and failure assessment to establish service intervals, replacement schedules, and total cost of ownership. Integrate comprehensive energy measurement—specific energy consumption ($\text{kWh}\cdot\text{t}^{-1}$), fuel consumption ($\text{L}\cdot\text{h}^{-1}$ and $\text{L}\cdot\text{t}^{-1}$), and engine load efficiency—for full techno-economic optimization.

3. **Alternative power systems and scale-up designs:**

Explore renewable energy options—solar-battery hybrid systems, diesel engines (20-30% better fuel efficiency), PTO connection to two-wheel tractors, or animal-drawn/pedal-powered alternatives—to improve operational flexibility, reduce fuel costs, and expand accessibility. Develop smaller (pedal-powered, $100\text{ kg}\cdot\text{h}^{-1}$) and larger (tractor-mounted, $1000\text{ kg}\cdot\text{h}^{-1}$) versions to serve diverse farmer categories from individual households to medium-scale commercial farms.

4. **Socio-economic impact evaluation and cooperative strengthening:**

Conduct

longitudinal studies of adopting cooperatives to measure changes in household income and food security, gender impacts on labour allocation and empowerment, local economic multiplier effects, and barriers to adoption. Develop targeted extension programs specifically for women's cooperative groups to maximize gender equity benefits from reduced labour burden (2-3 days to 3-4 hours per tonne).

5. **Ergonomic and safety improvements with policy integration:**

Implement systematic ergonomic assessment of operator posture, lifting requirements, and control interfaces, combined with safety analysis of guarding effectiveness and kickback protection. Advocate for policies that subsidize local fabrication, invest in polytechnic agricultural engineering training, establish quality standards for locally fabricated machinery, and facilitate microfinance credit access for farmer cooperatives to catalyze widespread adoption.

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