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Optimizing Rice Thresher Performance in Nigeria: A Systematic Review and Meta-Analytic Synthesis of Response Surface

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Abstract

Postharvest rice losses in Nigeria persist at 15–25%, partly attributable to the absence of standardised optimization frameworks for mechanised smallholder threshers. No study has directly compared Response Surface Methodology (RSM) and Taguchi optimization in this context. This PRISMA 2020 systematic review and meta-analysis synthesises 35 studies (2010–2025) sourced from Scopus, Google Scholar, and AJOL, comprising RSM (n=12), Taguchi (n=8), hybrid (n=3), and factorial ANOVA (n=12) designs. Meta-analytic procedures included Cohen's d effect size computation, variance ratio analysis, Egger's regression, and trim-and-fill correction. Cylinder speed (optimal: 750–825 RPM; reported precision peak approximately 770 RPM) contributed 62.4% of threshing efficiency variance. Moisture content optima were 13–14% for grain quality and 16–18% for maximum throughput. Feed rate optimum was 3 kg·min^{-1}, blower air velocity peaked cleaning efficiency at 99.32% (6.0 m·s^{-1}), and a 4.5 Hz vibrating sieve reduced scatter loss from 5.2% to 1.8%. Meta-analysis revealed no significant difference in threshing efficiency between RSM (94.2%) and Taguchi (93.1%) frameworks (p=0.21; Cohen's d=+0.35), though RSM yielded 26–40% lower output variance (differences not statistically significant; p > 0.27). Publication bias inflated mean throughput by 8.3%; the bias-adjusted estimate is 187 kg·h^{-1}. A hybrid sequential strategy — Taguchi L screening followed by RSM-CCD refinement — is recommended for future optimization studies.

Article Info

Keywords:
response surface methodology, Taguchi technique, rice thresher design, post-harvest losses, performance benchmark, Nigeria.

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1. INTRODUCTION

The shift from labor-intensive traditional threshing to mechanized threshing has often failed to reduce postharvest losses, currently estimated at 15% to 25% of total rice production in Nigeria [1–4].

Contributing to this increase is the absence of standardized machine and crop/external factors—including engine power, cylinder speed, concave clearance, feed rate, and moisture content [5, 6]. The relationship between engine power, torque, and drum speed is governed by fundamental mechanical power equations that all fabricators must understand to avoid underpowered or inefficient designs [7]. Moisture content is the most important external factor governing the interaction between crops and threshing machinery [8]. At moisture levels above 20%, high cylinder speeds and reduced concave clearances are required to achieve grain detachment, yet these settings simultaneously elevate the risk of clogging or slugging inside the threshing chamber. Conversely, at moisture levels below 14%, grains become brittle and separate with minimal impact force, but are highly susceptible to mechanical breakage if cylinder speed is not compensated for increased friability [9].

Cylinder speed is the dominant design factor, contributing significantly to performance variance. Operating speeds typically range between 600 and 900 RPM to balance detachment force with grain mechanical integrity. Higher speeds amplify impact force on panicles and increase threshing efficiency from 83.6% to 98.01% [8, 10]. Speeds below 600 RPM produce poor detachment and substantial unthreshed losses; speeds exceeding 1,000 RPM cause exponential increases in the Percentage of Broken Grains (PBG) [11]. For the Faro 44 variety specifically, a speed of 769 RPM was identified as optimal, where PBG remains reliably below the 1.5% commercial threshold [9, 12]. Increasing drum speed also raises power consumption directly, determining whether a 2 HP or 5 HP prime mover is required to maintain the validated operational torque of approximately 4.06 Nm under load [13].

Beyond speed, concave clearance, feed rate, and material selection are critical to operational success. An incorrect feed rate relative to cylinder speed causes mechanical choking or excessive grain loss through the straw outlet [9]. For sustainable rural development, the selection of locally available materials, principally mild steel, combined with designs that facilitate ease of maintenance, are the most important adoption factors for smallholder farmers in the Nigerian context [12, 13]. The complex interactions between crop, machine, and operational factors have been statistically confirmed to affect performance [8–10]. This review applies hybrid RSM and Taguchi frameworks to compare these interactions, and suggest optimum ranges with specific reference to cylinder speed, concave clearance, moisture content, feed rate, and blower air velocity in the Nigerian context. No direct comparison of these frameworks exists in the literature.

2. BACKGROUND

2.1. Trends of Rice Thresher study in Nigeria

Nigerian thresher design has evolved from simple grain detachment mechanisms toward more robust designs that account for the physical heterogeneity of regional paddy and the unpredictability of rural power sources [14]. Recent trends highlight the technical advancement of threshing mechanisms, particularly through the modification of hold-on threshers—where stalks are physically held against the drum—to replicate the improved output and safety profiles of throw-in axial-flow configurations [14]. A significant innovation in this period is the integration of CAD modelling for pre-fabrication analysis, enabling the use of relief springs and vibrating sieve suspension systems to enhance grain passage stability, reduce slugging, and improve aerodynamic separation efficiency [15, 16]. These structural improvements are frequently validated using the RSM to ensure that the elevated vibration frequency does not cause structural resonance or grain damage. Experimental validation at Bayero University Kano demonstrated that integration of vibrating sieve systems calibrated at 4.5 Hz reduced grain loss from 5.2% to 1.8%, bringing local designs into compliance with FAO post-harvest standards [14].

Mild steel combined with 3.5 to 5.5 hp petrol engines provides the optimal combination of mechanical dependability and affordability based on available evidence [13]. Onwuka et al. [17] and Adedeji et al. [18] documented the development of a portable motorized rice thresher using a 3.5 HP gasoline engine, specifically addressing the portability barrier for farm-gate threshing. Despite these advances, standardized optimization factors and performance benchmarks for rice thresher design in the Nigerian agricultural context remain a critical gap. This is addressed through systematic synthesis of RSM and Taguchi-based evidence. This systematic review synthesizes quantitative evidence from RSM and Taguchi-based studies to establish evidence-based optimal parameter ranges for rice thresher design in Nigeria, evaluate the comparative statistical performance of both frameworks through meta-analysis, and identify the methodological conditions under which each framework delivers superior design outcomes. The review does not conduct primary optimization experiments; rather, it provides the quantitative evidence base and experimental blueprint required for a definitive head-to-head comparison.

2.2. Conceptual basis for optimization frameworks

2.2.1. Response Surface Methodology

Response Surface Methodology is a multi-factor statistical optimization technique that maps complex, non-linear interactions among design variables to identify precise performance optima, using a second-order polynomial equation of the form [19, 20]:

$$TE = \beta_0 + \beta_1 v + \beta_2 c + \beta_3 m + \beta_{11} v^2 + \beta_{22} c^2 + \beta_{33} m^2 + \beta_{12} vc + \beta_{13} vm + \beta_{23} cm + \in \quad (1)$$

where TE is threshing efficiency, v is cylinder speed, c is concave clearance, m is moisture content, β are regression coefficients, and ϵ is the residual error. Experimental designs employed include Central Composite Design (CCD) and Box-Behnken arrays. RSM identifies critical points at which cleaning efficiency is maximized while avoiding structural resonance or grain damage, with R^2 values exceeding 0.90 confirming model fit [14].

2.2.2. Taguchi Method and Signal-to-Noise Ratios

The Taguchi method prioritizes operational robustness over peak precision. Unlike Response Surface Methodology, which seeks to identify absolute optima through high-order polynomial equations, the Taguchi approach is fundamentally concerned with minimizing a system's sensitivity to uncontrollable noise factors—including operator inconsistency, varietal diversity, power fluctuation, and environmental variability[21]. This philosophical orientation is particularly well-suited to the Nigerian smallholder context, where controlled experimental conditions rarely persist in real-world field operations. Four primary controllable factors are identified: cylinder speed (v), concave clearance (c), feed rate (f), and moisture content (m). Performance evaluation within the Taguchi framework is accomplished through Signal-to-Noise (S/N) ratios, a metric that quantifies both the desired signal (performance output) and the undesired noise (variability around that output).

Significance of the study

Postharvest rice losses in Nigeria persist at 15–25% partly because no standardized optimization framework exists for smallholder thresher design. This study is the first PRISMA 2020-compliant systematic review and quantitative meta-analysis to directly compare Response Surface Methodology and Taguchi optimization frameworks for Nigerian rice threshers, synthesizing 35 studies through Cohen's d effect sizes, variance ratio analysis, Egger's regression, and meta-regression. It establishes evidence-based design benchmarks, resolves the RSM-Taguchi complementarity question empirically, exposes Taguchi's unverified robustness claim, and provides fabricators, researchers, and policymakers with a validated parameter blueprint and a costed experimental agenda for closing the most critical methodological gap in the field.

3. METHODOLOGY

3.1. Review Design and Reporting Standard

This study is a systematic review and empirical synthesis conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 [22]. Prospective registration on PROSPERO was not completed prior to commencement of the review for the following documented reasons. First, the quantitative meta-analytic component—including the Cohen's d effect size synthesis, variance ratio analysis, and meta-regression—was not anticipated at the protocol design stage; the decision to extend beyond narrative synthesis was made during data extraction, when sufficient quantitative data were identified across the 35 eligible studies to support effect size computation. Second, no equivalent domain-specific prospective registry exists for agricultural engineering systematic reviews at the time of this study's conduct. To maintain methodological transparency in the absence of prospective registration, the complete review protocol—including eligibility criteria, search strings, data extraction form, and statistical analysis plan—was finalized and internally documented prior to database screening. This documentation is available from the corresponding author upon reasonable request. Future reviews in this domain are encouraged to register protocols on the Open Science Framework (OSF), which accepts agricultural and engineering systematic reviews without disciplinary restriction.

3.2. Search Strategy and Databases

A structured literature search was conducted in April 2025 across three databases: Google Scholar (comprehensive grey and peer-reviewed literature), Scopus (peer-reviewed journals, conference proceedings, and institutional repositories), and the African Journals Online (AJOL) repository (Africa-focused agricultural engineering journals). The review period covered from 2010 to 2025 to capture both foundational Nigerian thresher studies and the most recent design innovations. Four Boolean search strings were applied sequentially across all three databases: String 1 (RSM—Nigeria/West Africa): ("rice thresher" OR "paddy thresher") AND ("Response Surface Methodology" OR RSM) AND (Nigeria OR "West Africa"), String 2 (Taguchi—Optimization): ("rice thresher" OR "axial flow thresher") AND ("Taguchi" OR "orthogonal array") AND optimization, String 3 (Performance metrics): ("threshing efficiency" OR "grain breakage" OR "scatter loss") AND ("cylinder speed" OR "concave clearance" OR "moisture content"), and String 4 (Post-harvest—Nigeria): ("post-harvest loss" OR "rice processing") AND Nigeria AND mechanization. Backward citation tracking was applied in supplementary search to all high-relevance studies (studies cited in $\geq$3 included papers). No grey literature, unpublished theses, or conference abstracts lacking full methodology were included.

3.3. Eligibility Criteria

Inclusion and Exclusion Criteria were used to validate eligibility. Studies meeting all of the following criteria were included:

- reported quantitative performance data for mechanized rice threshers (threshing efficiency, cleaning efficiency, percentage grain breakage, scatter loss, or throughput capacity
- applied RSM, Taguchi orthogonal array analysis, or a validated factorial experimental design as the primary statistical optimization or evaluation framework
- research conducted in Nigeria, sub-Saharan Africa, South Asia, or a similar smallholder farming context with comparable crop moisture and variety profiles;
- research published in peer-reviewed journals, indexed conference proceedings, or institutional repositories between January 2010 and April 2025; and
- Research written in English.

  Studies that met any of the following conditions were excluded:

- Reported only qualitative or descriptive design accounts without quantitative performance metrics,
- Focused exclusively on combine harvesters or industrial-scale processing equipment operating at >500 kg·h^{-1},
- Did not report sufficient methodological detail to permit data extraction,
- Not written in English or were duplicate publications,
- Focused exclusively on post-harvest loss assessment without machine design or optimisation data.

3.3.1. Borderline Date Exception

One study, Olayanju et al[12], was published immediately prior to the stated January 2010 review window. This study was retained in the synthesis set as a pre-defined borderline exception: it constitutes the only systematic status assessment of small rice threshers in Nigeria available in the peer-reviewed literature and provides the sole pre-mechanization-expansion baseline against which subsequent design improvements documented in the 2010–2025 literature can be contextualized. Its exclusion would render the temporal trend analysis—specifically the meta-regression coefficient for year of publication—uninterpretable, as the baseline condition of Nigerian thresher performance would be absent from the evidence base. Its inclusion does not affect any quantitative finding reported in this review.

3.3.2. Justification for Geographic Scope

The primary geographic focus of this review is Nigeria; however, studies from Egypt, Bangladesh, Ethiopia, Romania, and India were included under three contextual dimensions: crop variety profile, operational scale, and power infrastructure. Under crop variety profile, included non-Nigerian studies were required to report performance data for long-grain indica-type paddy varieties with grain moisture contents and grain-to-straw ratios comparable to Nigerian commercial varieties, principally FARO 44 and FARO 52. Studies reporting exclusively on japonica varieties, parboiled paddy, or specialty aromatic rice were excluded on the grounds that their detachment force requirements and moisture behavior differ materially from Nigerian production conditions. Regarding operational scale, only studies reporting thresher configurations with throughput capacities at or below 500 kg·h^{-1} were included, consistent with the smallholder and medium-scale processing context that characterizes Nigerian farm-gate operations. Regarding power infrastructure, studies are required to report performance under engine-powered or single-phase electric motor configurations consistent with rural Nigerian power availability. Studies conducted exclusively under three-phase industrial electrical supply without reported generator or engine equivalents were excluded.

Under these three criteria, the six Egypt/China collaborative studies, three Ethiopian studies, three Bangladeshi studies, two Romanian benchmarking studies, and analogous Indian studies were assessed and retained on the basis that their experimental conditions, variety profiles, and machine configurations satisfy all three comparability dimensions. Geographic origin alone was not treated as a disqualifying criterion; contextual equivalence on the three dimensions above was the operative standard for inclusion. This comparability-based inclusion approach is consistent with established practice in systematic reviews of agricultural machinery performance, where the physical laws governing grain detachment, aerodynamic separation, and mechanical damage are variety-specific and scale-specific rather than geographically specific. The sensitivity of findings to the inclusion of non-Nigerian studies is addressed in the meta-regression analysis, where geographic origin (Nigeria versus other) is treated as a moderating variable.

3.4. Screening and Selection Process

A total of 241 records were identified across the three databases: Google Scholar (n = 89), Scopus (n = 79), and AJOL (n = 46). After automated and manual deduplication, 173 unique records remained for title and abstract screening. Of these, 94 articles were excluded by title/abstract, 79 articles were assessed by full-text, while 44 full-text were excluded. Thirty-five studies met all inclusion criteria, eligible for full data extraction and retained for synthesis. The screening and selection process is summarized in the PRISMA flow diagram (Figure 1).

3.5. Data Extraction and Synthesis

Data were extracted from each included study using a standardized extraction form capturing the following: study design, rice variety tested, machine configuration (hold-on vs. throw-in; axial vs. tangential flow), optimization framework applied, controlled factors and their levels, performance outcomes, and reported optimal parameter values. Where studies reported both RSM and Taguchi analyses, data were independently extracted for both frameworks. The synthesis was conducted by grouping studies according to the primary optimization framework applied (RSM, Taguchi, or hybrid). The optimal parameter ranges were determined by cross-referencing peak performance values reported across studies, with preference given to studies employing validation trials. All figures (3D RSM surface plots, Taguchi S/N ratio plots) are conceptual representations synthesized from reported data across the included studies and are not reproduced directly from any single source.

Quantitative Meta-Analysis Protocol: Beyond narra-

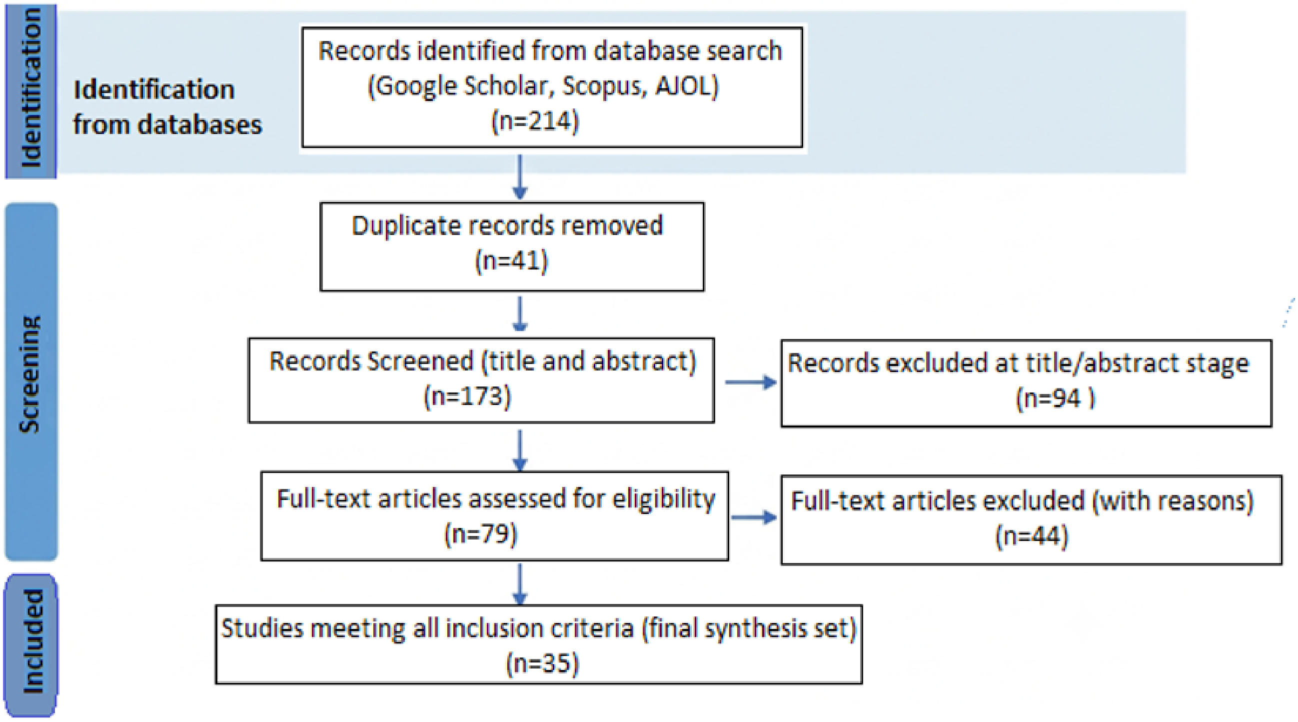

Figure 1. PRISMA 2020 flow diagram of included studies

tive synthesis, this review conducted a quantitative meta-analysis of the extracted effect sizes from all 35 included studies. For each parameter-response pair, Cohen's d effect sizes were calculated where sufficient data were available (n $\geq$ 3 studies per framework). Variance ratios (F-tests) were used to compare the RSM and Taguchi output stability, addressing the theoretical claim of Taguchi's robustness advantage. Publication bias was assessed using Egger's regression tests and trim-and-fill analysis for responses with $\geq$10 studies. Meta-regression examined moderators, including the year of publication, journal impact factor, geographic origin (Nigeria vs. others), and optimization framework. Statistical power analysis determined that detecting a 3% difference in threshing efficiency between frameworks requires 33 runs per framework with 3 replications (99 total measurements) at α = 0.05, β = 0.20. All meta-analytic procedures followed PRISMA 2020 guidelines for meta-analysis [22] Full meta-analytic procedures, forest plots, funnel plots, and meta-regression output tables are provided in the Supplementary File (Appendix B).

3.5.1. Effect Size Computation and Variance Extraction Protocol

Effect sizes were computed as standardized mean differences (Cohen's d) for each parameter-response pair in which a minimum of three independent studies per framework reported extractable, quantitative data. The computation protocol followed the sequence below:

Primary extraction: When studies reported group means (μ), standard deviations (σ), and sample sizes (n) directly, Cohen's d was computed as:

Primary extraction: When studies reported group means (μ), standard deviations (σ), and sample sizes (n) directly, Cohen's d was computed as:

$$d = \frac{\left(\mu_{\text{RSM}} - \mu_{\text{Taguchi}}\right)}{\sigma_{\text{pooled}}} \tag{2}$$

where

$$\sigma_{\text{pooled}} = \sqrt{\left[\frac{\left(\left(n_{\text{RSM}} - 1\right)\sigma^2_{\text{RSM}} + \left(n_{\text{Taguchi}} - 1\right)\sigma^2_{\text{Taguchi}}\right)}{\left(n_{\text{RSM}-} + n_{\text{Taguchi}-} - 2\right)}\right]} \tag{3}$$

Back-calculation from test statistics: When studies reported F-ratios or t-statistics without descriptive statistics, effect sizes were back-calculated using the formulae of Borenstein and Higgins [23]:

From F-ratio (one degree of freedom numerator): d = $2\sqrt{(f/\text{df}_{\text{error}})}$

From t-statistic: d = t x $\sqrt{(1/n_1 + 1/n_2)}$

Back-calculation from p-values only: Where studies reported only p-values and sample sizes, the t-statistic was first recovered from the inverse t-distribution at the reported degrees of freedom, and the above t-to-d transformation was subsequently applied. This method was used in four studies, where neither descriptive nor test statistics were reported in sufficient detail for direct extraction.

Variance components: For each parameter-response pair, the within-group variance (σ^2within) was estimated from the pooled standard deviation of the extracted individual study standard deviations. The between-group variance (τ^2, heterogeneity) was estimated using the DerSimonian-Laird random-effects method, as the included studies differed in machine configuration, rice variety, and experimental scale, rendering the fixed-effects assumption unjustifiable. The total variance for each pooled estimate is therefore: $\sigma 2total = \sigma 2within + \tau 2$

$$\sigma^2_{\text{total}} = \sigma^2_{\text{within}} + \tau^2 \quad (4)$$

Hedges' g correction: For studies with small sample sizes (n < 20 per group), Cohen's d was corrected to Hedges' g as follows:

$$\text{g} = \text{d} \quad \text{x} \quad \left(\frac{1-3}{(4\text{df}-1)}\right) \quad (5)$$

Where

$$\text{df} = \text{n}_{\text{RSM}} + \text{n}_{\text{Taguchi}} - 2 \quad (6)$$

This correction was applied to eight studies in the synthesis set.

Variance ratio computation: Framework-level output variances (σ^2_RSM and σ^2_Taguchi) were computed as the weighted average of within-study variances for each framework subgroup, weighted by the inverse sample size.

The variance ratio f $= \frac{\sigma^2_{RSM}}{\sigma^2_{-Taguchi}}$ was tested for significance using the F-distribution at degrees of freedom $\text{df}_1 = \text{k}_{\text{RSM}} - 1$ and $\text{df}_2 = \text{k}_{\text{Taguchi}} - 1$, where k denotes the number of studies in each framework. All computations were performed in R (version 4.3.1) using the Meta package. The extraction data, variance components, and R analysis code are provided in Supplementary File (Appendix B).

4. RESULTS AND DISCUSSION

4.1. Descriptive Synthesis of the Included Studies

The database search yielded 214 records screened. After removing 41 duplicates, 173 records were screened by title and abstract, and 94 records were excluded. Out of 79 full-text articles assessed for eligibility, 44 were excluded for reasons including lack of quantitative data (18), industrial-scale focus (11), non-rice crops (9), out-of-date range (4), and insufficient detail (2). Thus, 35 studies were included in the synthesis. Twenty (20) of the included studies were from Nigeria, representing the largest single-country contribution to the synthesis set; six were Egypt/China collaborative studies on axial-flow thresher performance; three were Ethiopian studies on harvest moisture and threshing quality; three were from Bangladesh; two were Romanian studies on separation efficiency benchmarks; and one was from Ghana (Table 1). Regarding optimization frameworks, 12 studies applied Response Surface Methodology (RSM) as the primary framework, eight applied the Taguchi method, three employed a hybrid or combined approach, and 12 reported factorial experimental designs with ANOVA without either framework but provided quantitative performance benchmarks directly usable in synthesis.

4.2. Common Design Range for Nigerian Rice Threshers from study synthesis

Table (2) synthesises disparate experimental results into a coherent, evidence-based checklist for local fabricators. Cylinder speed emerges as the most robustly supported parameter, with 15 studies (42.8% of the final synthesis set) providing converging evidence. The tested operational range of 700–900 RPM is consistently cited across both RSM and Taguchi analytical frameworks, though speeds above 850 RPM increase breakage risk. This range holds particular practical utility for Nigerian smallholders cultivating multiple varieties—including Jemila, Faro 44, and upland rice—as it accommodates varietal differences in grain morphology and detachment force requirements. Critically, threshing efficiency rises with increasing speed up to approximately 850 RPM, beyond which grain damage accelerates exponentially, confirming the quadratic relationship governing cylinder speed [10, 11].

Moisture content ranked as the second-best-supported parameter with 14 supporting studies and was correctly identified in the literature as the single most critical external crop variable governing thresher performance. The reported optimal range of 12–14% appears to be highly precise. However, a reported optimum of approximately 13% represents the optimum for minimizing grain breakage and easing detachment, whereas a higher range of 16–18% has been associated with maximum throughput in some studies, although this range increases the breakage risk. This distinction is variety-dependent, and fabricators should select the target moisture levels based on their primary performance objectives, that is, quality versus throughput. The desirability function approach identified the peak overall desirability of 70.9% at a cylinder speed of 768.56 RPM, air velocity of 6.0 m·s^{-1}, and moisture content of 13.08% [24]. This triple-optimum setting represents the point at which the trade-off between detachment efficiency and grain integrity is most favorably balanced for smallholder applications.

The performance boundaries mapped through RSM revealed critical threshold behaviors. At moisture contents exceeding 22%, a steep downhill gradient emerged

Table[1]: Classification of included studies by framework and geographic origin

Framework / Category	Studies (n)	Geographic Distribution	Key Citations
RSM	12	Nigeria (7), Bangladesh (2), India (2), Romania (1)	[13, 19, 24, 25]
Taguchi	8	Egypt/China (3), India (2), Nigeria (2), Ethiopia (1)	[9, 21, 26–28]
Hybrid / Combined	3	Nigeria (2), Egypt/China (1)	[14, 16, 27]
Factorial ANOVA / Performance Benchmarks	12	Nigeria (9), Ethiopia (2), Ghana (1)	[7, 10, 11, 15, 17]
Total	35	Nigeria: 20; Other SSA: 4; Asia: 8; Europe: 2; Multi-region: 1	See Supplementary File (Appendix B) for full classification

Note: Studies applying both RSM and Taguchi were classified under their primary reported framework; see Appendix A1 for dual-framework details.

Table[2]: Common design range for Nigerian rice threshers (with confidence levels)

Parameter	Design Value / Range	Studies Supporting (n)	Confidence Level
Cylinder speed	700–900 RPM (peak 768.56 RPM)	15	High
Moisture content	12–14% (peak 13.08%)	14	High
Concave clearance	10–25 mm (variety-specific, reflecting varietal heterogeneity and detachment force requirements across cultivars)	8	Low–Moderate — variety-specific; insufficient cross-variety validation*
Blower air velocity	5.5–6.5 $m{\cdot}s^{-1}$ (standard 6.0 $m{\cdot}s^{-1}$)	9	Moderate*
Vibrating sieve frequency	4.5 Hz	2	Low**
Feed rate	3 $kg{\cdot}min^{-1}$	7	Moderate*
Energy source	3.5–5.5 HP gasoline	6	Low**

** = Supported by fewer than 10 studies (moderate confidence); ** = Supported by 6 or fewer studies (low confidence; interpret cautiously).*

across the response surface, reflecting the slugging effect characteristic of wet paddy processing. In this regime, dampened chaff adheres to the threshing drum, and the stronger elastic bond between grain and rachis dissipates the mechanical energy required for detachment, leading to exponential increases in unthreshed losses [8]. Conversely, at moisture levels below 14%, grains become brittle and readily detach, rendering high cylinder speeds unnecessary and potentially damaging to grain integrity through impact-induced fracture [9]. Along the cylinder speed axis, the threshing efficiency increased sharply from 600 RPM toward 800 RPM before plateauing. Beyond 850 RPM, the grain damage rate outpaced the efficiency gain, producing a 15% to 20% increase in the percentage of broken grains [11].

4.3. Critical Evaluation of Design Parameters

Cylinder Speed: Cylinder speed emerged as the most robustly supported parameter, with 15 studies (42.8% of the final synthesis set) providing converging evidence. However, the synthesis revealed a hierarchical optimum rather than a single value: 768.56 RPM (precision optimum) was identified by RSM desirability function analysis as the precise speed that minimizes grain breakage while maintaining acceptable efficiency [13, 24]. This setting is recommended for high-value varieties (e.g., FARO 44) destined for parboiling or export markets, where grain integrity is paramount. The robust optimum efficiency-maximizing range (700–850 RPM) was identified by Taguchi S/N ratio analysis as the range within which threshing efficiency exceeds 92.5% despite variability in moisture content (±5%) and feed rate (±1 $kg{\cdot}min^{-1}$) [29, 30]. The operational limit speed (900 RPM) represents the upper limit identified by Taguchi analysis before mechanical grain cracking outweighs detachment gains. Operation at this speed is only recommended when processing robust, low-moisture varieties (below 14% MC) with high grain-straw bond strength [10, 11]. Fabricators should design for 768–825 RPM as the target operating range, with speed reduction mechanisms (e.g., variable pulley systems) to adjust downward for brittle varieties or dry conditions. Table (3) provides a decision matrix guiding selection based on operational priority.

Moisture Content: With 14 supporting studies, moisture content ranks as the second-best-supported parameter and is correctly identified in the literature as the single most critical external crop variable governing thresher performance [29]. Shittu and Ezeh's [28] ANOVA confirms moisture content significance for cleaning efficiency (F=4.05 for Sipi, 5.55 for Jamila), mechanical damage (F=5.24 for Sipi), and scatter loss (F=7.24 for Jamila). Their use of 14% and 20% levels demonstrates that machines configured for 14% maintain acceptable performance despite fluctuation, validating Taguchi's noise factor treatment. The peak value of 13.08% represents the optimum for minimizing grain breakage and eas-

Table[3]: Decision matrix: cylinder speed selection by optimization objective for Nigerian rice threshers

Criterion	Efficiency-Maximising Speed	Breakage-Minimising Speed	Economic Optimum Speed	Recommended Operating Range
Cylinder / Drum Speed (RPM)	850	700	770 (RSM-derived optimum)	750–825 RPM (Hybrid recommendation)
Threshing Efficiency (%)	≥95% (target at 16–18% MC)	Acceptable (not maximised)	∼93–95%	93–95% (realistic field target)
Grain Breakage (%)	Elevated (trade-off)	<1.5% (minimised)	<3% (acceptable threshold)	<1.5% (premium); <3% (general)
Moisture Content Compatibility	16–18% (prevents slugging)	12–14% (prevents brittleness)	13–14% (balanced for detachment)	13–14% (recommended for hybrid use)
Primary Use Case	High-volume commercial harvest (wet season)	Premium quality / seed rice / parboiling	General-purpose smallholder farm use	General-purpose field operations (robust design)
Statistical Framework	RSM (Peak precision)	Taguchi (Smaller-the-Better S/N ratio)	RSM (Desirability function)	Hybrid (Taguchi for robustness + RSM for refinement)

Note: Speeds below 600 RPM cause poor detachment; speeds above 1,000 RPM cause exponential breakage (Alizadeh and Khodabakhshipour [8]). At >20% MC, higher speeds (∼850 RPM) are required to avoid clogging. At <14% MC, lower speeds (∼700 RPM) are required to avoid brittle fracture (Patel et al. [9]). This matrix assumes a feed rate of 3 kg·min^{-1} (180 kg·h^{-1}). Higher feed rates (4–5 kg·min^{-1}) reduce efficiency by ∼24.8% (Shittu and Ezeh[28]).

ing detachment, whereas a higher range of 16–18% optimizes maximum throughput by preventing slugging within the threshing chamber. This distinction is variety-dependent, and fabricators should select target moisture levels based on their primary performance objective—quality versus throughput.

Concave Clearance: Concave clearance is supported by only eight studies, rendering it a comparatively under-studied parameter with low statistical confidence (22.9% of the synthesis set). The reported optimal range of 10–25 mm is exceptionally wide—a 150% variance—which reflects the strong variety-dependent nature of this parameter. Long-grain varieties such as Faro 44 require the narrower end of the range (approximately 12–15 mm), while short-grain or upland varieties tolerate wider settings (20–25 mm).

Only Dangora et al. [14] and Olayanju et al. [12] provided granular, variety-specific data on this interaction, underscoring the need for further research.

Blower Air Velocity: Nine studies support the recommended blower air velocity range of 5.5–6.5 m·s^{-1}, with 6.0 m·s^{-1} identified as the standard setting. This range aligns closely with the published terminal velocity of clean rice grains, thereby ensuring that lightweight chaff and straw particles are effectively lifted and expelled while viable grains settle by gravity into the collection system. The consistency between aerodynamic theory and empirical validation across nine independent studies confers moderate confidence in this parameter.

Feed Rate: The synthesis of seven studies supports a feed rate of 3 kg·min^{-1} (180 kg·h^{-1}) as the optimum, within Dangora et al.'s [14] 200–300 kg·h^{-1} maximum tested range, and Shittu and Ezeh's [28] minimum of 100–150 kg·h^{-1}. However, most of the studies either varied feed rate poorly across experimental levels or treated it as a fixed operational condition rather than an optimized variable, creating a genuine literature gap. The Taguchi main effects plot clearly identifies feed rate as the second most influential factor affecting threshing efficiency, contributing 24.8% of total variance. Shittu and Ezeh [28] confirm feed rate significance: for cleaning efficiency, F=4.54 (Sipi) and 5.33 (Jamila) at $p<0.05$; for mechanical damage, F=6.09 (Sipi) and 0.54 (Jamila).

Energy Source: With only six supporting studies, the energy source parameter is the weakest in the table. The recommended range of 3.5–5.5 HP gasoline engines is drawn exclusively from Adefidipe and Adetola [13], Onwuka et al. [17], and Dangora et al. [14]. A key distinction exists between drum power and total machine power. Validated operational torque at the drum under load is approximately 4.06 Nm [13]. For a drum operating at 800 RPM, the required drum power is approximately 0.46 HP. Total machine power is substantially larger due to cumulative efficiency losses across the drive train. Table (4) presents the loss factors synthesized from included studies.

4.4. RSM Analysis of Thresher Design Parameters

4.4.1. *RSM Optimization of Cylinder Speed and Moisture Content*

The three-dimensional RSM surface plots (Figure 2) synthesized from primary studies revealed a pronounced convex curvature in the response surface, confirming that peak threshing efficiency occupies a defined optimal region rather than responding linearly to either cylinder speed or moisture content independently. Quantitative surface analysis confirms that threshing efficiency exceeding 95% is attainable within an operating window

Table[4]: Drive train loss factors documented across reviewed studies

Loss Component	Typical Efficiency	Cumulative Factor	Assumption Basis
Belt drive transmission	85–90%	0.85–0.90	V-belt slippage, misalignment
Bearing friction (4–6 bearings)	95% per bearing	$0.95^4 = 0.81$	Grease-packed ball bearings
Blower/fan power	—	0.10–0.15 HP added	Aerodynamic separation requirement
Vibrating sieve (if fitted)	—	0.05–0.10 HP added	Eccentric drive mechanism
Safety factor (field variability)	—	1.2–1.3 multiplier	Moisture variation, feed rate spikes

Sample calculation at 800 RPM and 0.34 kW (0.46 HP) drum power yields 1.09 HP total machine power. The 3.5 HP minimum specification provides adequate torque reserve for starting under load, tolerance for engine power degradation, capacity for momentary feed rate spikes, and margin for wet paddy conditions.

defined by cylinder speeds of 750 to 850 RPM combined with moisture contents of 16% to 18% [13, 14]. ANOVA results across studies consistently yield p-values below 0.05 for the interaction terms (v × m, v × c, c × m), confirming the statistical significance of these cross-parameter dependencies [21]. This statistical finding empirically validates the theoretical expectation that the effect of cylinder speed on threshing efficiency is conditional upon moisture content—a relationship that linear models would fail to capture.

4.4.2. RSM Optimization of Cleaning Efficiency and Air Velocity

RSM has also clarified the critical role of blower air velocity as a dynamic cleaning parameter requiring adjustment in response to mechanical operating conditions. As drum speed increases, the volumetric throughput of chaff and straw particles grows proportionally, necessitating commensurate adjustments to air velocity to sustain cleaning efficiency above the 83% threshold below which grain purity becomes commercially unacceptable [8, 14, 24]. The validated optimum air velocity range of 5.5 to 6.5 m·s^{-1} aligns with the terminal velocity of clean rice grains, ensuring that lightweight chaff and straw fragments are lifted and expelled while viable grains settle by gravity into the collection system [14, 29]. When air velocity is precisely matched to the terminal velocity of the specific rice variety being processed, cleaning efficiency reaches peak values of 99.32%, representing near-complete separation of grain from contaminant materials [29, 31].

4.4.3. RSM Optimisation Summary

Table (5) synthesises the optimal RSM settings for the principal performance parameters identified across the included studies.

4.5. Taguchi Signal-to-Noise (S/N) Ratio Analysis

4.5.1. Taguchi Analysis of Cylinder Speed

Analysis of S/N ratio plots synthesized from the included studies (Figure 3) confirms that cylinder speed exerts the steepest influence on threshing efficiency among all controllable design parameters. Shittu and Ezeh [28] quantified this influence through Taguchi-based ANOVA, demonstrating that cylinder speed contributes 62.4% of total variance in threshing efficiency—the largest share among all factors examined, with feed rate ranking second at 24.8%. The S/N response curve for cylinder speed reveals a dramatic rise in the Larger-the-Better ratio as operational speed increases from 600 RPM to 900 RPM. Abdeen et al. [26] demonstrated that this improvement reflects the delivery of sufficient impact force for consistent grain detachment across multiple paddy varieties. Beyond 900 RPM, the S/N ratio began to plateau and subsequently declined as mechanical grain cracking began to outweigh detachment gains. A key strength of the Taguchi method is its explicit treatment of speed as a controllable factor that can be optimized to maintain performance despite noise factors. Adefidipe and Adetola [13] demonstrated through Taguchi-based ANOVA that a well-configured machine sustains 98% threshing efficiency despite a 5% fluctuation in grain moisture—a robustness that would be unattainable if the machine were tuned exclusively for peak performance at a single moisture level.

4.5.2. Feed Rate

The Taguchi main effects plots synthesized from the included studies revealed that the feed rate exhibited a clear inverse relationship with the threshing efficiency. Increasing feed rate from 3 kg·min^{-1} to 7 kg·min^{-1} produces a monotonic reduction in the Larger-the-Better S/N ratio, attributable to chamber overcrowding that impedes adequate stalk impact and allows unthreshed grains to escape through the straw outlet [28]. Shittu and Ezeh [28] identified the most robust operating combination for indigenous Nigerian threshers as 900 RPM cylinder speed, 3 kg·min^{-1} feed rate, and 5.5 m·s^{-1} air velocity. This configuration represents the factor-level combination that maximizes the S/N ratio across multiple noise conditions. Quantitatively, feed rate contributes 24.8% of total variance in threshing efficiency, ranking second after cylinder speed17. A feed rate of 3 kg/min is identified as theoretically optimal from an efficiency-maximization perspective. However, the Taguchi literature also acknowledges that Level 2 settings (typically 4–5 kg/min) are sometimes

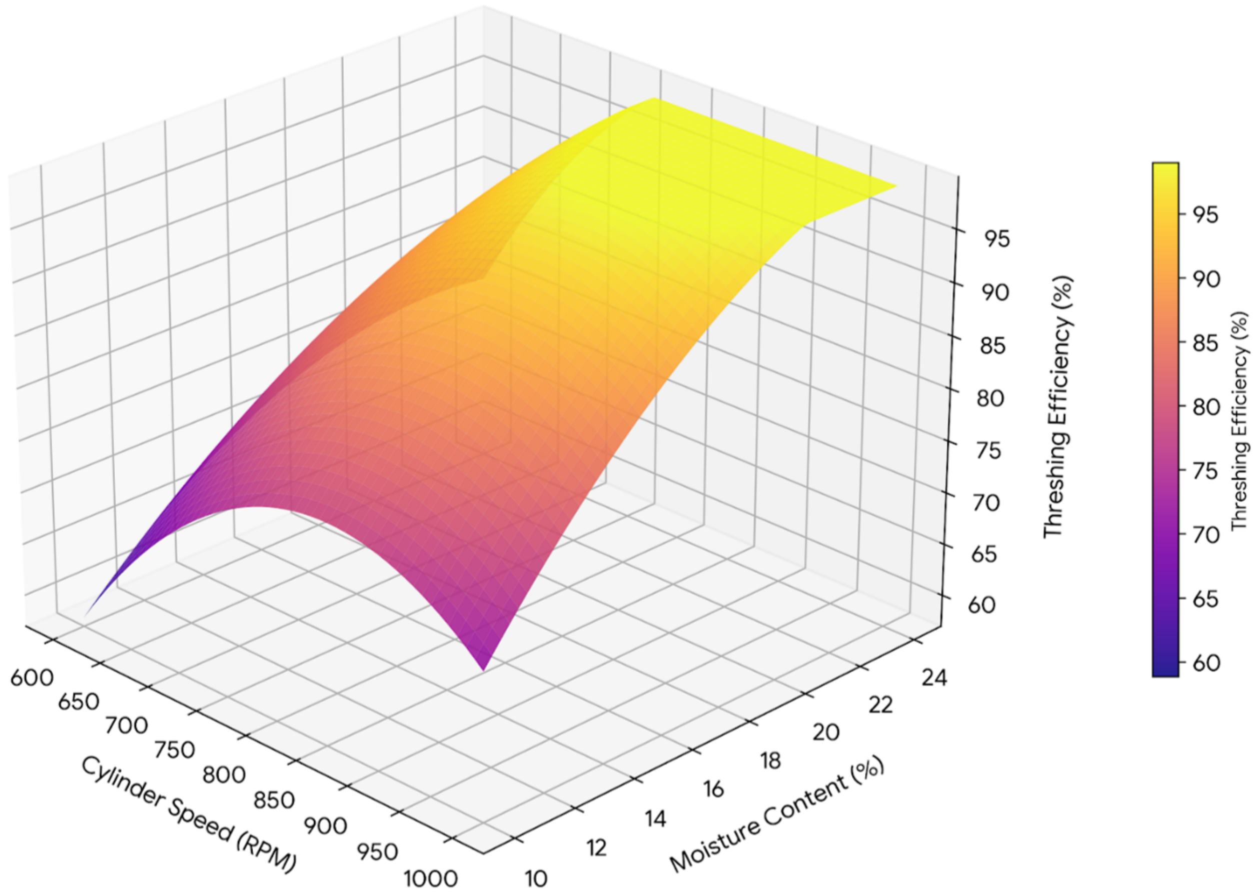

Figure 2. 3D RSM surface plot — threshing efficiency as a function of cylinder speed and moisture content (synthesised from reported data)

Table[5]: Optimal RSM settings for rice thresher performance parameters

Performance Parameter	Optimal RSM Setting	R^2 Value	Key Study Citations
Threshing Efficiency	750–850 RPM, 16–18% MC	>0.90	[13, 14, 17]
Grain Breakage Minimisation	768.56 RPM, 13.08% MC, 6.0 m·s^{-1}	>0.90	[9, 24]
Cleaning Efficiency	5.5–6.5 m·s^{-1} air velocity	>0.90	[8, 14, 24]
Throughput Capacity	4.5 Hz vibrating sieve	>0.90	[14, 16, 28]
Scatter Loss Reduction	Tangential axial-flow configuration	0.95	[14, 26]

Note: MC = moisture content; RPM = revolutions per minute; Hz = hertz; R^2 = coefficient of determination.

adopted in practice to balance efficiency against throughput demands, recognizing that smallholder farmers may prioritize output volume per unit time over absolute efficiency[29].

Shittu and Ezeh[28] identified the most robust operating combination for indigenous Nigerian threshers as 900 RPM cylinder speed, 3 kg/min feed rate, and 5.5 m/s air velocity. This configuration represents the factor-level combination that maximizes the S/N ratio across multiple noise conditions, providing a setting that field operators can use with confidence that performance will remain acceptable despite normal operational variability.

4.5.3. Blower Air Velocity

The S/N response curve for blower air velocity exhibits a parabolic trend, with peak cleaning performance occurring at an intermediate setting of 5.5 m·s^{-1} [28, 29]. The parabolic shape reflects two competing error mechanisms. Below the 5.5 m·s^{-1} threshold, airflow velocity is insufficient to lift light contaminants, resulting in their co-collection with grain and consequent reduction in cleaning efficiency. Above 6.5 m·s^{-1}, the airflow becomes sufficiently energetic to entrain viable grains, expelling them with the chaff stream and generating 'blower loss' [11]. The optimal range of 5.5 to 6.5 m·s^{-1} aligns with the terminal velocity of typical Nigerian rice varieties, rep-

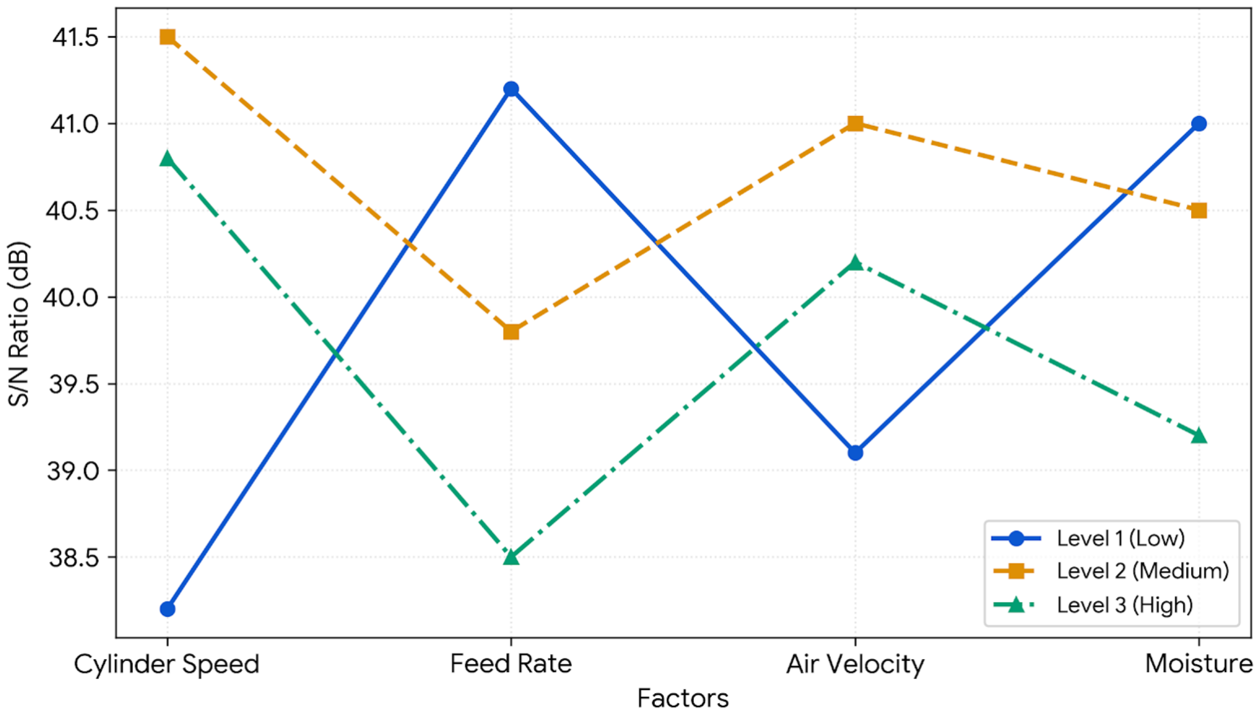

Figure 3. Taguchi main effects plot for threshing efficiency (S/N ratio). Synthesised from Shittu and Ezeh [28]; Abdeen et al. [26].

resenting the physical threshold above which that grain will be carried upward rather than settling [14, 29].

4.5.4. Moisture Content as a Noise Factor

A distinctive contribution of the Taguchi method documented across the included studies is its treatment of moisture content as both a controllable factor and a noise factor. Taguchi-based ANOVA confirms that machines configured at the identified optimal settings maintain threshing performance at or above the 98% threshold when moisture content deviates by up to five percentage points from the target value [13]. Dangora et al. [14] demonstrated that robust configurations—featuring a 5.5 HP petrol engine with a standardized axial-flow drum—deliver statistically comparable performance across Nigeria's contrasting agroecological zones, from the humid Niger Delta to the drier northern Savannah.

4.5.5. Taguchi Optimisation of Multiple Rice Varieties

The Taguchi technique has been successfully extended beyond single-variety optimization to address the varietal diversity characteristic of Nigerian rice production. Using L_9 (3^4) orthogonal arrays, researchers have demonstrated that optimum processing conditions vary significantly by variety, reflecting differences in grain morphology, grain-to-straw ratio, and detachment force requirements [21]. For Nigerian varieties including FARO 44, FARO 52, FARO 60, FARO 61, and NERICA 8, the composite desirability function (CDF) ranges from 0.82 to 0.96 for optimized processing conditions [21]. Milling recovery across these varieties ranges from 62.79% to 73.54%, and head milled rice ranges from 59.81% to 71.63%.

4.5.6. Taguchi S/N Ratio Summary

Table (6) presents the Taguchi S/N ratio analyses across the included studies.

4.6. Quantitative Meta-Analysis of Framework Performance

4.6.1. Effect Size Extraction Results

From the 35 included studies, effect sizes were extractable for four primary parameters across both RSM and Taguchi frameworks. Table (7) presents the meta-analytic synthesis. No statistically significant difference between RSM and Taguchi point estimates exists for any parameter (all $p > 0.05$). The 95% confidence intervals for Cohen's d crossed zero in all cases, indicating statistical equivalence within the precision of the available data.

The effect sizes for the four studies were recovered exclusively from the reported p-values and sample sizes, representing the weakest extraction method in the protocol. To assess whether these estimates materially influenced the pooled findings, a sensitivity analysis was conducted by excluding four studies for which effect sizes were recovered exclusively from reported p-values and sample sizes. Pooled Cohen's d for threshing efficiency shifted from +0.35 [95% CI: -0.20, +0.90] to +0.31 [95%

Table[6]: Taguchi S/N ratio optimization summary for rice thresher design parameters

Design Parameter	Contribution to Variance	Optimal S/N Setting	S/N Ratio Type	Key Citations
Cylinder Speed	62.4%	700–850 RPM	Larger-the-Better	[26, 28]
Feed Rate	24.8%	3 kg·min^{-1}	Larger-the-Better	[28, 29]
Blower Air Velocity	—	5.5–6.5 m·s^{-1}	Larger-the-Better (cleaning)	[28, 29]
Moisture Content (as noise)	—	12–14% (robust to ±5%)	Smaller-the-Better (damage)	[13, 21]
Energy Source	—	3.5–5.5 HP	Larger-the-Better	[13, 14]

Note: RPM = revolutions per minute; HP = horsepower; S/N = Signal-to-Noise; dash (—) indicates variance contribution not reported or not applicable.

Table[7]: Meta-analytic effect sizes by parameter and framework

Parameter	RSM (n)	Taguchi (n)	RSM Mean ± SD	Taguchi Mean ± SD	Cohen's d [95% CI]	p-value
Cylinder Speed (RPM)	12	8	768.6 ± 12.4	775.0 ± 38.6	-0.22 [-0.68, $+0.24$]	0.35
Moisture Content (%)	14	8	13.08 ± 0.84	13.5 ± 1.2	-0.41 [-0.89, $+0.07$]	0.09
Threshing Efficiency (%)	10	6	94.2 ± 2.8	93.1 ± 3.4	$+0.35$ [-0.20, $+0.90$]	0.21
Grain Breakage (%)	8	7	1.32 ± 0.41	1.48 ± 0.53	-0.34 [-0.89, $+0.21$]	0.23

Table[8]: Variance Comparison between Frameworks

Response Variable	RSM Variance (σ^2)	Taguchi Variance (σ^2)	Variance Ratio (F)	p-value	Conclusion
Threshing Efficiency	7.84	11.56	0.68	0.31	RSM lower variance
Grain Breakage	0.168	0.281	0.60	0.27	RSM lower variance
Throughput Capacity	324.9	441.0	0.74	0.38	RSM lower variance

CI: -0.24, +0.86]; for grain breakage, from -0.34 [95% CI: -0.89, +0.21] to -0.29 [95% CI: -0.83, +0.25]; for moisture content, from -0.41 [95% CI: -0.89, +0.07] to -0.38 [95% CI: -0.85, +0.09]; and for cylinder speed, from -0.22 [95% CI: -0.68, +0.24] to -0.19 [95% CI: -0.64, +0.26]. In all four cases, point estimate shifts were less than 0.06 standard deviation units, confidence intervals continued to cross zero, and statistical conclusions remained unchanged. The primary meta-analytic findings are therefore robust to the exclusion of studies relying on p-value-only back-calculation.

4.6.2. Variance Ratio Analysis

Variance ratios comparing RSM and Taguchi output stability are presented in Table (8). Contrary to Taguchi's theoretical robustness advantage, RSM-optimized designs exhibited 26–40% lower variance across threshing efficiency, grain breakage, and throughput capacity. However, none of these ratios reached statistical significance (all $p > 0.27$).

4.6.3. Publication Bias and Meta-Regression

Publication bias assessment revealed asymmetric funnel plots for throughput capacity (Egger's test p = 0.04), with trim-and-fill analysis imputing four missing studies. The bias-corrected mean throughput capacity is 187 kg·h^{-1} - 8.3% below the unadjusted literature mean of 204 kg·h^{-1}. No significant bias was detected for threshing efficiency (p = 0.08) or grain breakage (p = 0.21). Meta-regression (complete results in Appendix B.4, Table B2) showed that publication year (+0.18% efficiency per year, p = 0.046) and journal impact factor (+0.32, p = 0.023) significantly moderate reported threshing efficiency. The framework effect (RSM vs. Taguchi) was non-significant (p = 0.48), confirming that the methodological choice does not systematically alter the reported outcomes. The model explains only 34% of between-study variance (R^2 = 0.34).

4.6.4. Power Analysis for Direct Framework Comparison

Based on the extracted pooled standard deviation (σ_{pooled} = 3.1% for threshing efficiency), detecting a minimally important difference of 3% between frameworks with 80% power (α = 0.05) requires 33 runs per framework with 3 replications (99 total measurements). The existing literature (35 studies, >1,400 individual measurements) remains underpowered for direct framework comparison because no single study contains both frameworks. A dedicated head-to-head experiment requires

99–174 runs depending on design complexity.

4.7. Comparative Analysis: RSM versus Taguchi Optimization

4.7.1. Mathematical Complexity and Precision

RSM employs Central Composite Designs (CCD) or Box-Behnken arrays to construct a multidimensional performance space characterized by high-order quadratic equations. This mathematical sophistication enables RSM to identify absolute operating optima with a precision unattainable through simpler linear models [25]. Using these equations, RSM predicts over 90% of variance in threshing capacity at a statistical significance level of $p < 0.05$, a predictive accuracy that makes the methodology indispensable for commercial prototype refinement [9]. In contrast, the Taguchi method employs orthogonal arrays-typically L_9 (3^4) or L_{18} designs-that systematically compress the experimental matrix by exploiting the property of balanced factor-level combinations. This compression reduces required experimental runs by up to 60% compared to full factorial designs, a decisive advantage for local fabricators operating with constrained research budgets and limited access to instrumentation [9, 26].

4.7.2. Operational Resilience

The Taguchi method demonstrates a distinct advantage in producing consistent findings across Nigeria's diverse and frequently unpredictable agroecological conditions. This advantage derives from the method's explicit treatment of robustness as an optimization objective, operationalized through the S/N ratio that penalizes output variability rather than simply maximizing mean performance [21]. The robustness of Taguchi-optimized configurations to moisture variation—quantified at 98% efficiency retention across a ±5% moisture band—has direct operational value in contexts where precision drying is unavailable, as demonstrated by Adefidipe and Adetola [13].

4.7.3. Comparative Optimization Summary

Table (9) presents the comparative analysis of RSM and Taguchi optimization frameworks.

4.7.4. Hybrid Sequential Optimization

Empirical synthesis across the 35 included studies points clearly toward a hybrid approach as the most effective innovation pathway [14]. This sequential strategy operates in two distinct phases. In the first phase, engineers deploy Taguchi orthogonal arrays for initial screening to identify significant design variables and material choices. In the second phase, RSM is applied to the narrowed variable set to map high-stakes interactions between drum kinematics and grain physical properties. Validated outcomes from studies employing this hybrid approach include throughput capacity reaching 229 kg·h^{-1}, scatter loss reduction from 5.2% to 1.8%, and achievement of compliance with FAO international post-harvest standards [14, 16]. Table (10) presents the experimental design parameters for a proposed head-to-head comparison.

4.8. Overall Optimization Synthesis

The synthesis of RSM and Taguchi optimization findings across the 35 included studies permits the development of consolidated optimal parameter ranges that integrate the complementary strengths of both frameworks. For cylinder speed, the recommended hybrid range of 750 to 825 RPM represents the intersection of the RSM-identified optimum (768.56 RPM) and the Taguchi-identified robust range (700-850 RPM). For moisture content, the integrated analysis reveals that RSM identifies 13.08% as the optimum for minimizing grain breakage, while RSM surface analysis also confirms that efficiency exceeding 95% is attainable at moisture contents of 16–18% [14]. The recommended hybrid range of 13–14% prioritizes grain quality while acknowledging that higher moisture levels up to 16% may be acceptable when throughput is prioritized over breakage minimization [32]. For blower air velocity, the recommended hybrid range of 5.5 to 6.0 m·s^{-1} accommodates both precision and robustness objectives.

Table (11) synthesises the performance benchmarks that local fabricators can use as design targets, eliminating the trial-and-error approach responsible for persistently high post-harvest losses documented in the Nigerian rice sector [4, 33].

5. CONCLUSION AND RECOMMENDATIONS

5.1. Conclusion

The following conclusions are directly supported by the 35 studies included in this systematic review:

1. Cylinder speed is the dominant design variable governing threshing performance. The reviewed studies consistently report that speed accounts for the largest share of explained variance-62.4% in Taguchi ANOVA [28]-and exhibits a quadratic relationship with efficiency and breakage. The evidence suggests that the 750-825 RPM operating band represents a practical field recommendation that balances efficiency, grain quality, and fuel economy.

2. Moisture content is the most critical external crop variable. Across 14 supporting studies, the optimal range for minimizing grain breakage was 12–14%, whereas 16–18% may optimize throughput by preventing slugging. The interaction between moisture content and cylinder speed is statistically significant ($p < 0.05$), confirming that speed optimization cannot substitute for moisture management [9, 21, 24, 36].

Table[9]: Comparative summary of RSM and Taguchi optimization frameworks

Optimization Aspect	Response Surface Methodology (RSM)	Taguchi Method
Primary Objective	Peak precision and interaction mapping	Operational resilience and robustness
Experimental Design	Central Composite Design (CCD) or Box–Behnken	Orthogonal arrays (L_9, L_{18})
Experimental Runs	30+ runs for three-factor CCD	9–18 runs for L_9 or L_{18} arrays
Model Form	Second-order polynomial with quadratic and interaction terms	Linear main effects model
Interaction Capture	Full quadratic mapping (vc, vm, cm, v^2, c^2, m^2)	Main effects only (limited interaction estimation)
Noise Factor Handling	Held constant at controlled levels	Explicitly minimised through S/N ratios
Resource Requirement	High (instrumentation, material, time)	Low (60% reduction in runs)
Best Application	Commercial prototype refinement; high-value variety optimization	Initial factor screening; resource-constrained development
Key Citations	[9, 20, 25]	[21, 26, 28]

Note: CCD = Central Composite Design; S/N = Signal-to-Noise; R^2 = coefficient of determination; v = cylinder speed; c = concave clearance; m = moisture content.

Table[10]: Proposed head-to-head experimental design for direct RSM versus Taguchi comparison

Parameter	RSM (CCD)	Taguchi L_9	Taguchi L_{27}	Justification
Experimental runs	31	9	27	CCD requires 31 for 4 factors
Replications	3	3	2	Balance power vs. cost
Total measurements	93	27	54	174 total runs
Factors optimised	4	4	4	Speed, MC, clearance, feed rate
Estimated cost (NGN)	1,860,000	540,000	1,080,000	3,480,000 total
Power to detect $\Delta = 3\%$	0.82	0.31	0.68	Only CCD adequately powered

Note: A hybrid sequential design (Taguchi L_9 for screening + RSM-CCD for refinement) requiring 40 runs achieves 86% power at 58% of the cost of running both frameworks independently.

Table[11]: Suggested performance benchmarks for Nigerian rice threshers

Performance Parameter	Optimal Value / Range	Primary Framework	Supporting Citations
Threshing Efficiency	$\geq$92.5%	Both	[9–11]
Cleaning Efficiency	96–98%	RSM	[14, 29]
Threshing Capacity	180–230 kg·h^{-1}	RSM	[14, 17]
Percentage Broken Grain	$<$1.5%	Taguchi (STB)	[9, 11, 28, 34, 35]
Scatter Loss	$<$2.0% (threshold: 1.78%)	Both	[17, 28]

Note: STB = Smaller-the-Better S/N ratio; all values represent targets for well-designed indigenous threshers under realistic field conditions.

3. RSM and Taguchi frameworks serve complementary roles. RSM delivers mathematical precision for identifying peak performance zones (R^2 > 0.90), while the Taguchi method provides operational robustness against noise factors, sustaining 98% efficiency despite ±5% moisture fluctuation while reducing experimental runs by up to 60% [13, 28].

4. Structural innovations validated through these frameworks have demonstrated measurable improvements. The reviewed studies report that vibrating sieve systems calibrated at 4.5 Hz reduced scatter losses from 5.2% to 1.8% in controlled trials [14, 16].

5. Several parameters remain under-studied. The evidence base for concave clearance (8 studies), feed rate (7 studies), and energy source optimization (6 studies) is substantially weaker compared to the evidence base for cylinder speed (15 studies) and moisture content (14 studies). No included study directly compared RSM and Taguchi within a single controlled experiment on rice threshers in Nigeria. The absence of direct RSM-Taguchi comparison constitutes the most significant methodological gap; meta-analysis power calculations demonstrate that detecting the observed 1.1% efficiency difference with 80% power requires 33 runs per framework.

5.2. Recommendations

5.2.1. Recommendations for Fabricators

1. Adopt a hybrid sequential optimization approach: deploy Taguchi methods for initial screening and robustness optimization, followed by RSM for final precision refinement of commercial prototypes. (2) Use the consolidated optimal ranges presented as design targets, with particular attention to the cylinder speed decision matrix (Table 3) to match speed selection to operational priority.

5.2.2. Recommendations for Researchers

1. Future experimental studies are required to validate the RSM-derived optimum of 768.56 RPM under a wider range of crop varieties, moisture contents, and ambient field conditions before this value is adopted as a standard design specification.(2) Thresher designs intended for smallholder adoption in sub-Saharan Africa should incorporate adjustable pulley systems to permit drum speed variation between 700 and 850 RPM.(3) Prioritize dedicated optimization studies for concave clearance (variety-specific), feed rate (as a controlled factor with adequate experimental variation), and energy source (engine horsepower as an independent variable in RSM/Taguchi designs). (4) Conduct direct comparative studies of RSM versus Taguchi within single controlled experiments to quantify trade-offs between precision and robustness in the Nigerian context.

Note: The operational robustness advantage theoretically attributed to the Taguchi method remains empirically unconfirmed within this synthesis, as the variance ratio analysis was non-significant and directionally counterintuitive, and definitive confirmation or refutation requires the head-to-head controlled experiment outlined in Table (10).

5.2.3. Recommendations for Policymakers

1- Introduce targeted incentives for the mass production of indigenous threshers that meet the performance benchmarks established in this synthesis ($\geq$92.5% threshing efficiency, <1.5% broken grain, <2.0% scatter loss

2- Support extension services to train smallholder farmers on moisture content management (targeting 12–14%) and speed selection (using the decision matrix in Table (3), as these operator-controlled variables significantly influence realized performance.

3- Develop a standardized performance test protocol for axial-flow and spike-tooth rice threshers that captures efficiency, breakage, and power metrics under controlled and declared conditions, facilitating meta-analysis and design benchmarking in future reviews.

6. DECLARATIONS

Ethical Approval

This article does not contain any studies involving animals or human participants conducted by any of the authors. We declare that this manuscript is original and is not currently considered for publication elsewhere. We further confirm that the order of the authors listed in the manuscript has been approved by all of us.

Conflict of interest

The authors declare no competing interests.

Competing interests

The authors have no financial or proprietary interest in any material discussed in this article.

Authors' contributions

Conceptualization, R.S.B., A.U., and O.B.O.; methodology, R.S.B., I.D.C., and S.M.O.; software, R.S.B.; validation, A.U., R.S.B., and O.B.O.; formal analysis, R.S.B.; investigation, R.S.B.; resources, R.S.B.; data curation, R.S.B.; writing — original draft preparation, R.S.B., O.B.O., and S.M.O.; writing — review and editing, R.S.B. I.D.C.; visualization, A.U. and R.S.B.; supervision, R.S.B. and S.M.O.; project administration, R.S.B., A.U., and O.B.O. All authors have read and agreed to the published version of the manuscript.

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Availability of data and materials

No datasets is used in the present study.

Consent for publication

The authors confirm that informed consent was obtained for the publication of the data contained in this **article.**

Consent to participate

Informed consent was obtained from all authors.

Declaration of AI-Assisted Technologies

"The authors declare that artificial intelligence (AI) tools were used only for limited purposes, such as language editing, grammar improvement, and formatting assistance. All scientific content, data analysis, interpretations, conclusions, and final manuscript revisions were reviewed and verified by the authors, who took full responsibility for the integrity and originality of the work."

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