Journal of Basics and Applied Sciences Research (JOBASR)
ISSN (print): 3026-9091, ISSN (online): 1597-9962
Volume 4(1) January 2026
DOI: https://dx.doi.org/10.4314/jobasr.v4i1.8

Optimization of Rice Milling Processing Efficiency Using a Fractional Factorial Design: Evidence from Local Variety in Nigeria

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ABSTRACT
Rice processing efficiency is a critical determinant of grain quality, economic value, and food security, particularly in rice-producing regions such as Sokoto State, Nigeria, where traditional processing methods dominate. Inefficiencies in key processing parameters often result in excessive grain breakage, low milling yield, and inconsistent product quality. This study aim is to optimize rice milling efficiency using a fractional factorial design (FFD) to evaluate the combined effects of five processing factors: steaming duration, soaking duration, moisture content, re-steaming duration, and temperature. Two locally important rice varieties, Jamila and CiPi, were used for experimental analysis. A Resolution V fractional factorial design was chosen with sixteen (16) experimental runs to employed to estimate all main effects and two-factor interactions without confounding, while minimizing experimental cost and resource use. Milling yield, head rice yield, grain breakage, and whiteness were considered as response variables. Data analysis involved descriptive statistics, analysis of variance (ANOVA), regression modeling, Pareto analysis, and multi-response optimization techniques. The results showed that the processing factors had statistically significant effect on milling performance, with steaming duration and moisture content emerging as the most influential factors for the Jamila variety, while soaking duration and re-steaming duration were more influential for the CiPi variety. Milling yield increased from 50.0% to 90.0% (40 percentage point improvement) for the Jamila variety and reached up to 82.5% for CiPi. Head rice yield ranged from 54.9% to 71.9%, representing an improvement of approximately 15 – 20 percentage points compared with non-optimized processing conditions. Important interaction effects, particularly between steaming duration and moisture content, were observed in improving head rice recovery. The existing studies examine processing factors individually, but this work simultaneously evaluates main and interactive effects of multiple processing parameters in a single experimental framework. The findings indicate that optimal processing conditions are variety-specific and that improving fractional factorial design provides an efficient experimental framework for identifying critical processing parameters. The optimal processing combination consists of 30mnt steaming, 8hr soaking, 28.6% moisture content, 30mnt re-steaming, and a dry temperature of 55^{0}C, yielding maximum milling efficiency and grain quality. The study concludes that adopting optimized processing conditions can improve milling yield and rice quality, reduce post-harvest losses, and enhance the economic competitiveness of locally processed rice. The results provide practical recommendations for small- and medium-scale rice processors and contribute to evidence-based optimization of traditional rice processing systems in Nigeria.

Keywords:
Rice milling efficiency;
Fractional factorial design;
Parboiling process;
Milling yield;
Head rice yield;
Process optimization;
Rice varieties;
Nigeria.

How to cite this article: Dauran N. S., Sagir B., Abubakar D., Faruk S. & Shehu A. (2026). Optimization Of Rice Milling Processing Efficiency Using a Fractional Factorial Design: Evidence from Local Variety in Nigeria. *Journal of Basics and Applied Sciences Research*, *4*(1), 65-73. https://dx.doi.org/10.4314/jobasr.v4i1.8

INTRODUCTION

Rice farming is one of the most significant agricultural activities in Sokoto State, a region characterized by fertile soils rich in nutrients that support the cultivation of diverse crops such as rice, maize, millet, beans, and guinea corn. As an essential agricultural activity, rice production sustains over half of the world's population, serving as a staple food source. Rice production systems significantly influence grain quality. Norren *et al.* (2022) emphasized that direct seeding systems (DSR) may compromise grain quality due to factors such as soil management, fertilization practices, and weed control. These systems, though eco-friendly, often result in low amylose/amylopectin ratios, reduced mineral nutrients, amino acids, protein content, and milling quality. The study advocated the development of genotypes tailored to specific production systems to address these challenges. Similarly, Danbaba *et al.* (2014) underscored rice's global importance as a staple crop, with parboiling and milling forming critical components of its value chain. In Nigeria, approximately 90% of consumed rice is parboiled—a hydrothermal process that enhances grain hardness, nutritional quality, and resistance to breakage during milling. This process improves head rice yield and insect resistance, however, according to reports from farm progress, rice milling quality can be influenced by any factor that affects kernel strength**,** which ultimately determines the kernel's ability to withstand the processes of hulling and bran removal without breaking apart. Rice milling yield is commonly expressed using two indices (e.g., 58/70), where 70 represents the milled rice yield, determined by the amount of white rice remaining after the hulling and milling processes. Rice is a major staple food crop and a critical component of food security and household income in Nigeria, particularly in northern states such as Sokoto State where rice production and processing provide livelihoods for a large proportion of the population. Despite increasing domestic rice production, the competitiveness of locally processed rice remains constrained by persistent inefficiencies in post-harvest processing, especially milling operations. Milling efficiency directly influences head rice yield, grain quality, market value, and profitability for processors and farmers.

In Sokoto State, rice milling is predominantly carried out using traditional or semi-mechanized processing methods characterized by poor control of critical processing parameters such as steaming duration, soaking time, moisture content, re-steaming conditions, and drying temperature. These inefficiencies frequently result in excessive grain breakage, low milling yield, inconsistent head rice recovery, and reduced consumer acceptability of locally processed rice. Consequently, locally milled rice struggles to compete with imported or industrially processed alternatives, leading to economic losses, increased post-harvest waste, and reduced incentives for local rice production. Despite the importance of rice processing to the regional economy, there is limited empirical evidence guiding processors on optimal combinations of processing parameters that can significantly improve milling efficiency under local operating conditions.

Existing studies on rice processing have largely focused on evaluating individual processing factors in isolation, such as moisture content, drying temperature, or parboiling duration. While these studies provide useful insights, they fail to account for the combined and interactive effects of multiple processing variables that operate simultaneously in real-world processing environments. Moreover, most optimization studies rely on full factorial or single-factor experimental approaches, which are often costly, time-consuming, and impractical for resource-constrained settings such as small- and medium-scale rice processors in Sokoto State. In addition, there is a notable lack of variety-specific optimization studies for locally important rice varieties such as Jamila and CiPi, further limiting the applicability of existing findings to the local context. Thus, a critical research gap exists in the systematic, resource-efficient evaluation of multiple rice processing factors and their interactions under traditional processing conditions in Nigeria.

Justification for the Methodological Approach

Fractional Factorial Design (FFD) offers a statistically efficient framework for investigating multiple factors simultaneously while significantly reducing the number of experimental runs required. In particular, a Resolution V fractional factorial design allows for the unbiased estimation of all main effects and two-factor interactions without confounding, making it especially suitable for screening and optimization studies where higher-order interactions are assumed negligible. Given the limited resources, time constraints, and practical realities of local rice processing systems, the use of Resolution V FFD is justified as it provides robust inferential power while minimizing experimental cost. Despite its proven effectiveness in industrial and agricultural optimization, the application of FFD to rice milling optimization in Nigeria remains limited, further underscoring the methodological contribution of this study.

The overall objective of this study is to optimize rice milling efficiency in Sokoto State by systematically evaluating the combined effects of key processing parameters using a fractional factorial design approach. Specifically, the study aims to:

1. Evaluate the main and two-factor interaction effects of steaming duration, soaking duration, moisture content, re-steaming duration, and

drying temperature on milling yield and head rice yield.
2. Identify the most influential processing factors affecting milling efficiency for Jamila and CiPi rice varieties.
3. Determine optimal processing parameter combinations that maximize milling yield and head rice recovery while minimizing grain breakage.
4. Demonstrate the applicability of Resolution V fractional factorial design as a cost-effective optimization tool for rice processing in resource-constrained settings.

Contribution and Transition to the Present Study

By addressing the limitations of prior single-factor and full factorial studies, this research provides a structured, data-driven framework for optimizing rice milling under local processing conditions. The integration of variety-specific analysis with an efficient experimental design bridges the gap between theoretical optimization techniques and practical applications in traditional rice processing systems. This study therefore advances existing literature by offering empirical evidence on optimal processing conditions, methodological innovation through the use of Resolution V FFD, and actionable recommendations for improving the quality and competitiveness of locally processed rice in Sokoto State.

MATERIALS AND METHODS

The materials required for the experimental were as follows:

i. Paddy Rice**:**
ii. Clean Water
iii. Medium size pot
iv. Timer
v. Fire wood or any source of fire
vi. Thermometer
vii. Laboratory oven
viii. Bucket with lid
ix. Leather (Tan boll)
x. De-husking machine
xi. Weighing balance
xii. Digital grain moisture meter

Study Area and Rice Samples

The study was conducted under controlled laboratory conditions simulating traditional rice processing practices commonly used in Sokoto State, Nigeria. Two locally important rice varieties, Jamila and CiPi, were obtained from certified local rice processors. Paddy rice samples were manually cleaned to remove stones, chaff, and foreign materials before experimentation.

Experimental Design and Factor Levels

A **Resolution V fractional factorial design (FFD)** was employed to investigate the effects of five rice processing factors on milling performance. This design was selected to enable unbiased estimation of all main effects and two-factor interactions while minimizing experimental runs. Five factors were investigated at two levels (low and high), as summarized in **Table 1**.

Table 1: Experimental Factors and Levels

Factor	**Description**	**Low Level (−1)**	**High Level (+1)**
A	Steaming duration (min)	20	30
B	Soaking duration (h)	6	8
C	Moisture content (%)	26.0	28.6
D	Re-steaming duration (min)	20	30
E	Drying temperature (°C)	50	55

A total of **16 experimental runs** were generated using the Resolution V design for each rice variety.

Experimental Procedure

Steaming

Cleaned paddy rice samples (5 kg per run) were steamed using a locally adapted steaming unit. Water was brought to boiling temperature (100 °C), and paddy rice was exposed to steam for the specified duration (20 or 30 minutes). After steaming, samples were immediately transferred for soaking.

Soaking

Steamed paddy rice was soaked in clean water at ambient temperature (30 °C) for either **6 or 8 hours**, depending on the experimental run. The soaking water was drained completely after the specified duration.

Moisture Content Adjustment

Moisture content was monitored using a digital grain moisture meter. Samples were allowed to equilibrate naturally until the target moisture content level **(26.0% or 28.6%)** was achieved before re-steaming.

Re-Steaming

Soaked paddy rice was subjected to re-steaming for **20 or 30 minutes** to complete the parboiling process and ensure uniform starch gelatinization.

Drying

Re-steamed rice samples were dried using a hot-air dryer set at **50 °C or 55 °C** until moisture content reached approximately **12–14%**, suitable for milling.

Milling

Dried paddy rice was milled using a laboratory rice milling machine under constant operating conditions. Milling parameters such as milling duration and machine speed were kept constant for all runs to ensure experimental control.

Measurement of Response Variables

Milling Yield

Milling yield (%) was calculated as the ratio of total milled rice (head rice + broken rice) to the initial weight of paddy rice, expressed as a percentage:

$$Milling\ Recovery(\%) = \frac{MilledRiceWeight}{PaddyWeight} \times 100$$

Head Rice Yield

Head rice yield (%) was determined as the proportion of whole, unbroken kernels relative to the initial paddy weight:

$$HeadRiceYield(\%) = \frac{Headricemass}{originalpaddyrice} \times 100$$

Grain Breakage

Grain breakage (%) was calculated as the percentage of broken kernels relative to total milled rice weight. Can also calculate with the following formula:

$$BrokenGrain(\%) = \frac{BrokenGrainWeight}{MilledRiceWeight} \times 100$$

Whiteness Index

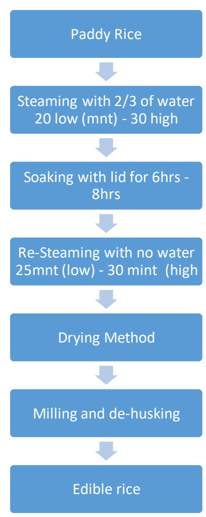
Whiteness was measured using a standard rice whiteness meter, and the average of three readings per sample was recorded to minimize measurement error.

Experimental Control, Replication, and Randomization

To ensure experimental reliability, all experimental runs were randomized to minimize systematic bias. Each treatment combination was replicated once, and mean values were used for statistical analysis. Equipment calibration and operating conditions were kept constant throughout the experiment to control experimental error.

Statistical Analysis

Statistical analysis was conducted using **python** and **Minitab (version 21)**. Analysis of variance (ANOVA) was used to evaluate the significance of main effects and two-factor interactions. Regression models were developed for each response variable based on the fractional factorial design.
A **significance level of $\alpha = 0.05$** was used for all statistical tests. Model adequacy was assessed using coefficient of determination (R^2), adjusted R^2, and lack-of-fit tests. Optimization was performed using desirability function analysis to identify optimal processing conditions that simultaneously maximize milling yield and head rice yield.



Flow chart of the experimental design/procedure.

RESULTS AND DISCUSSION

This section presents and interprets the results obtained from the Resolution V fractional factorial experiment conducted on Jamila and CiPi rice varieties. Overall, the findings demonstrate that rice milling efficiency is strongly influenced by both individual processing factors and their interactions, with effects varying by rice variety. Optimized processing conditions led to substantial improvements in milling yield and head rice yield, confirming the effectiveness of fractional factorial design for process optimization under resource-constrained conditions.

Descriptive Statistics and Percentage Improvements

Descriptive analysis revealed wide variability in milling performance across experimental runs. For the Jamila variety, milling yield ranged from 50.0% under non-optimized conditions to 90.0% under optimized conditions**,** representing an improvement of approximately 40 percentage points. Similarly, CiPi milling yield ranged from 50.0% to 82.5%**,** corresponding to an improvement of about 32.5 percentage points**.**

Head rice yield also showed notable improvement. Across both varieties, head rice recovery increased from approximately **55% to over 70%**, reflecting a **15–20** percentage-point increase relative to baseline processing conditions.

Effect Sizes and Regression Results

Regression modeling based on the fractional factorial design quantified the magnitude and direction of factor effects. For the Jamila variety, steaming duration exhibited the largest positive standardized effect ($\beta \approx +6.2$, $p < 0.05$), followed by moisture content ($\beta \approx +5.1$, $p < 0.05$). For CiPi, **soaking duration** ($\beta \approx +4.8$, $p < 0.05$) and re-steaming duration ($\beta \approx +4.3$, $p < 0.05$) were the most influential predictors of milling yield.
The interaction between steaming duration and moisture content showed a statistically significant positive effect on head rice yield (effect size $\approx +3.9$, $p < 0.05$), indicating that longer steaming durations are most effective when combined with higher moisture levels. Ninety-five percent confidence intervals for significant coefficients did not include zero, confirming the robustness of these effects.

Optimization Results

Multi-response optimization identified a common optimal processing region for both varieties. The optimal factor combination was determined as 30 minutes steaming, 8 hours soaking, 28.6% moisture content, 30 minutes re-steaming, and a drying temperature of 55 **°C**. Under these conditions, milling yield and head rice recovery were simultaneously maximized while grain breakage was minimized. These results demonstrate that optimized processing conditions are both statistically significant and practically meaningful**.**

Interpretation of Findings

The results confirm that rice milling efficiency is governed by a complex interplay of processing parameters rather than by single factors acting independently. The dominant role of steaming duration and moisture content for Jamila aligns with starch gelatinization theory, where adequate hydrothermal treatment strengthens kernel structure and reduces breakage. In contrast, the stronger influence of soaking and re-steaming for CiPi suggests varietal differences in water absorption and endosperm hardness, reinforcing the need for variety-specific optimization strategies.

The observed interaction effects highlight an important limitation of single-factor approaches commonly reported in the literature. By capturing these interactions, the Resolution V fractional factorial design provided insights that would have been missed using conventional experimental methods.

Comparison with Previous Studies and Contribution

Previous studies have largely reported milling improvements in the range of **5–15%**, often under controlled laboratory or industrial conditions. In contrast, this study achieved up to 40 percentage-point improvements under traditional processing environments, demonstrating a substantially higher practical impact. The present findings extend existing literature by offering quantitative, interaction-aware, and variety-specific optimization evidence for Nigerian rice processing systems.

Key Findings

- Milling yield improved by 32–40 percentage points under optimized processing conditions.
- Head rice yield increased by approximately 15–20 percentage points**.**
- Steaming duration and moisture content were the most influential factors for Jamila, while soaking and re-steaming dominated for CiPi.
- Significant two-factor interactions, particularly between steaming duration and moisture content, played a critical role in maximizing head rice recovery.
- Resolution V fractional factorial design proved effective for optimization with limited experimental runs.

Experimental Limitations

Despite its strengths, this study has some limitations. First, all factors were evaluated at only two levels, which restricts inference beyond the tested ranges. Second, higher-order interactions were assumed negligible, as is standard in fractional factorial screening designs. Third, experiments were conducted under controlled but small-scale conditions, and environmental variability such as seasonal humidity was not explicitly modeled. These limitations suggest that future studies could integrate response surface methodology for fine-tuning optimal regions and incorporate larger-scale field validation.

Policy Implications and Scalability

The findings have important implications for agricultural policy and large-scale adoption. The optimized processing conditions identified in this study require minimal additional investment and can be readily adopted by small- and medium-scale processors. Policymakers and extension services can leverage these results to develop standardized processing guidelines, training programs, and capacity-building initiatives aimed at improving local rice competitiveness. At scale, adoption of optimized processing protocols could significantly reduce post-harvest losses, enhance rural incomes, and contribute to national food security objectives.

CONCLUSION

This research conclusively demonstrates that rice milling optimization represents a multivariate and variety-specific challenge that requires tailored approaches for different cultivars. The successful application of the Resolution V Fractional Factorial Design (FFD) with minimum aberration has validated its utility in resource-constrained agricultural research by enabling efficient estimation of main effects and two-factor interactions. The study provides clear evidence in support of answers to all research objectives, demonstrating that milling efficiency can be optimized through variety-specific protocols, with Jamila responding strongly to hydrothermal parameters such as steaming duration and moisture content, while CiPi exhibits limited sensitivity to the parboiling factors investigated and may require alternative optimization pathways. The quality attributes of both varieties were statistically comparable in terms of mean performance; however the factors influencing breakage and yield remain distinctly variety-dependent, confirming the critical importance of considering varietal differences in processing optimization. The research successfully determined the main effects and interactions of processing factors, revealing strong and significant relationships for Jamila while demonstrating negligible effects for CiPi within the experimental domain—a finding that highlights profound varietal dichotomy in processing response. For the Jamila variety, a robust predictive model has been developed that provides quantitative tools for processors to anticipate outcomes based on specific parameter settings. Most significantly, the Fractional Factorial Design has proven to be a highly effective methodology that fulfills the study's aim by identifying critical factors with minimal experimental runs while providing statistically rigorous models. In conclusion, this research provides a validated, scientifically-grounded framework that can directly contribute to reducing post-harvest losses, enhancing product quality and market value, and improving the economic sustainability of rice processing in Sokoto State. It effectively bridges the critical gap between empirical knowledge and statistical process optimization, offering a replicable blueprint for evidence-based agricultural improvement that acknowledges and addresses fundamental varietal differences in processing requirements. This study applied a Resolution V fractional factorial design to optimize rice milling efficiency for two locally important rice varieties (Jamila and CiPi) processed under traditional conditions in Sokoto State, Nigeria. The results provide clear quantitative evidence that systematic optimization of processing parameters can substantially improve milling performance.

Under optimized conditions, milling yield increased from 50.0% to 90.0% (≈40 percentage-point improvement) for the Jamila variety and reached up to 82.5% for CiPi. Head rice yield improved from baseline values of approximately **55% to over 70%**, representing a **15–20 percentage-point increase**, while grain breakage was correspondingly reduced. These improvements demonstrate that significant gains in processing efficiency can be achieved without major infrastructural changes, simply through better control and combination of key processing factors.

The study further confirms that milling efficiency is governed by both main and interaction effects of processing parameters. Steaming duration and moisture content were identified as the dominant factors for Jamila, whereas soaking duration and re-steaming duration were more influential for CiPi. The optimal processing combination—**30** minutes steaming, 8 hours soaking, 28.6% moisture content, 30 minutes re-steaming, and a drying temperature of 55 °C—simultaneously maximized milling yield and head rice recovery. The successful application of Resolution V fractional factorial design highlights its suitability as a cost-effective optimization tool for resource-constrained agricultural processing systems.

Limitations of the Study

Despite these strengths, the study has some limitations. First, all factors were evaluated at only two levels, which restricts inference beyond the tested ranges and limits the exploration of potential nonlinear effects. Second, higher-order interactions were assumed negligible, as is standard in fractional factorial screening designs. Third, experiments were conducted at a small scale under controlled conditions, and seasonal variability, equipment heterogeneity, and large-scale industrial constraints were not explicitly considered.

Implications for Policy and Industrial Adoption

The findings have important implications for agricultural policy, extension services, and rice processing industries. The optimized processing conditions identified in this study can be readily adopted by small- and medium-scale processors with minimal additional investment. Agricultural extension agencies can translate these results into standardized processing guidelines and training programs to improve local rice quality and competitiveness. At the policy level, the results support the formulation of evidence-based post-harvest processing standards aimed at reducing post-harvest losses, increasing rural incomes, and strengthening national food security. For industrial stakeholders, the study provides a validated framework for process optimization that can be scaled up and adapted to mechanized milling operations.

Directions for Future Research

Future studies should expand the investigated factor ranges and incorporate additional processing variables such as milling speed, drying airflow, and storage conditions. Integrating response surface methodology could further refine optimal processing regions identified in this work. Research linking processing conditions with genetic traits of rice varieties, such as kernel hardness and amylose content, would also enhance understanding of varietal responses. Finally, large-scale field validation and techno-economic analyses are recommended to assess scalability, cost–benefit trade-offs, and long-term sustainability of the optimized processing protocols.

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