Effect of harvest moisture content and thresher operational parameters on rice milling quality

S.T. Hailemesikel[1,*], M. Alebachew[2], M.A. Delele[3,4], A.N. Ali[1], S.W. Fanta[3], G. Kidanemariam[1]

(1. Bahir Dar University, Bahir Dar Institute of Technology, Faculty of Mechanical and Industrial Engineering, Bahir Dar, P.O.Box 26, Ethiopia;
2. Ethiopian Institute of Agricultural Research, Fogera National Rice Research and Training Center, Woreta, P.O.Box 1937, Ethiopia;
3. Bahir Dar University, Bahir Dar Institute of Technology, Faculty of Chemical and Food Engineering, Bahir Dar, P.O.Box 26, Ethiopia;
4. Leibniz Institute for Agricultural Engineering and Bioeconomy (ATB), Potsdam, Eyth-Allee 100,14469 , Germany)

Abstract: High Post-harvest losses are a major challenge for rice production in sub-Saharan Africa. Threshing grain damage is one of the crucial factors affecting the quality and quantity losses of rice. This study investigated the effects of grain moisture content (MC), drum peripheral speed (DS), and spike arrangement (SS) on head rice yield (HRY) for three Ethiopian grown rice varieties (VAR), taking into consideration the initial condition of the grain. Experiments were conducted using a factorial design with four factors, and three replications. The results indicated that all the main effects (VAR, MC, DS, SS) and some of the interaction effects of the independent variables significantly impacted HRY and milling breakage. *Ediget* variety had higher HRY and lower milling breakage, whereas *Nerica-4* had lower HRY and higher milling breakage compared to the other two varieties. As MC increased from 11.44% to 24.01%, the least square mean HRY increased from 42.5% to 62.4% and milling breakage decreased from 21.9% to 6.8%, respectively. An increase in drum peripheral speed resulted in a decrease in HRY and an increase in milling breakage. Decreasing the spike spacing resulted in lower HRY and higher milling breakage. The harvest moisture content was identified as the most critical factor affecting HRY and milling breakage followed by drum peripheral speed and spike spacing. The results of this study can be used to develop effective strategies to minimize rice grain damage during mechanical threshing so as to improve milling quality.

Keywords: rice threshing, moisture content, drum peripheral speed, spike spacing, head rice yield, milling breakage

Citation: Hailemesikel, S. T., M. Alebachew, M. A. Delele, A. N. Ali, S. W. Fanta, and G. Kidanemariam. 2025. Effect of harvest moisture content and thresher operational parameters on rice milling quality. Agricultural Engineering International: CIGR Journal, 27(4):261-276.

1 Introduction

Rice, Oryza sativa L., is the fastest emerging cereal crop in sub-Saharan Africa (SSA) and the second most important source of energy in Africa (Arouna et al., 2021). Rice production is increased from 26.8 million MT in 2011 to 37.2 million MT in 2021 in Africa (FAO, 2023). However, the total demand for rice in Africa exceeds local production, and 40% of the rice consumed is imported (Zenna et al., 2017; Saito et al., 2023; Yuan et al., 2024). Furthermore, the consumption rate of rice is expected to increase by 130% in 2035 compared to 2010 (Seck

---

Received date: 2025-03-04 **Accepted date:** 2025-09-16

***Corresponding author: Solomon Tekeste Hailemesikel.** Bahir Dar University, Bahir Dar Institute of Technology, Faculty of Mechanical and Industrial Engineering, Bahir Dar Ethiopia. Email: soltektata@gmail.com.

et al., 2012), highlighting the urgency for African rice producers to increase their production capacity considerably to meet the ever-increasing demand using local produce.

Despite the increasing rice production in Africa, little attention has been given to postharvest handling practices. Current postharvest rice handling practices in Africa result in a physical loss of about 15%-25% and a financial loss of 20%–30% due to poor quality (Seck et al., 2012). In SSA, up to 50% qualitative loss is reported (Kebede et al., 2019), and the postharvest loss of rice in SSA in 2018 was estimated to be US$ 10.24 billion (Ndindeng et al., 2021), which is equivalent to 47.63% of the expected total production. Quantitative loss before and during harvesting was identified as the main cause, followed by qualitative loss along the entire value chain. Local rice in Africa, due to poor post-harvest practices, contains more than 50% broken rice and is of lower quality than imported rice (Nahemiah et al., 2021; Musa et al., 2024). This has led to the Ethiopian rice being sold at a lower price than imported rice in the domestic market (Manful, 2010).

Threshing practice is one of the most crucial factors affecting postharvest rice quality and quantity losses. Rice threshed by mechanical threshers is prone to grain damage, including grain breakage and fissuring, whose extent varies with machine-crop parameters. Improper threshing operation can lead to a higher rate of breakage, resulting in lower head rice yield (HRY). HRY, is milled rice comprised of kernels three-fourths or more the original kernel length (USDA, 2009). HRY is expressed as a percentage of the original dried rough rice mass and varies with various pre-milling factors, including rice variety, harvest moisture content, and threshing parameters.

Recent studies continue to affirm and expand upon the foundational work of Dilday (1989), who investigated the effects of grain moisture content (MC) and cylinder speed on rice milling quality using a Vogel sample thresher across eleven rice varieties. His findings revealed significant differences in milling yield among varieties, cylinder speeds, and grain moisture contents, with HRY notably higher at a cylinder speed of 600 rpm compared to 1000 rpm. Similarly, Esgici et al. (2020) and Feliz et al. (2005) studied effects of cylinder speeds on grain damage in combine harvester and found that as the cylinder speed increased the percentage of damaged kernels increased significantly. This phenomenon occurs because higher peripheral speeds increase the impact force exerted on the grains during threshing. Such forces can exceed the kernel's mechanical resistance, leading to the formation of internal micro-cracks and damage that results in breakage during the subsequent milling process (Yang et al., 2023; Liu et al., 2024)

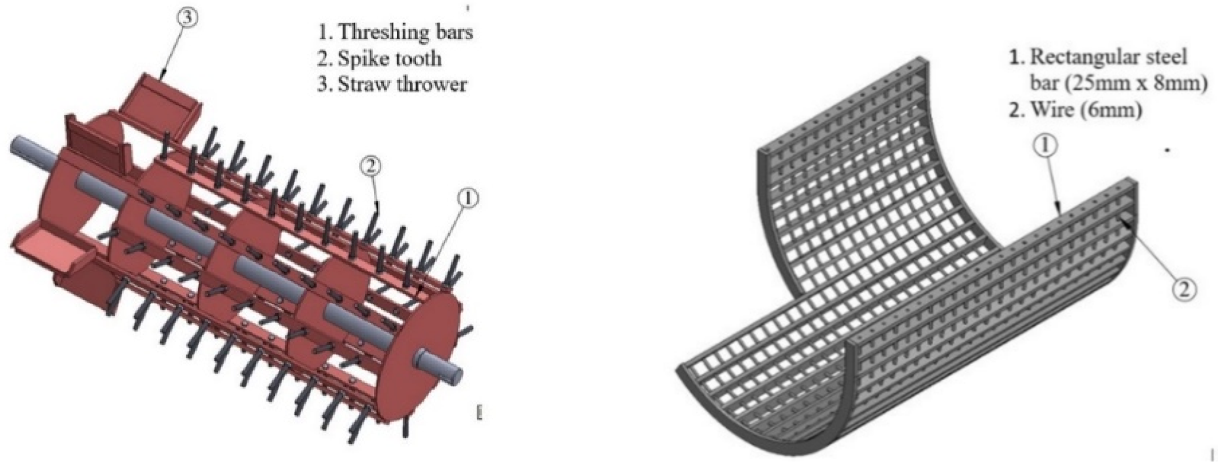
Numerous studies have demonstrated the profound impact of MC at harvest on HRY. Generally, harvesting rice at lower MC levels leads to reduced milling quality due to increased kernel fissuring and susceptibility to breakage (Berrio and Cuevas-Perez, 1989; Dilday, 1989; Siebenmorgen et al., 1992; Andrews et al., 1993; Thompson and Mutters, 2006; Nalley et al., 2016). However, the relationship between harvest MC and HRY is not uniform across all types of rice and is highly dependent on the specific cultivar. For example, Siebenmorgen et al. (2007) determined that the optimal harvest MC range for maximizing HRY varied significantly between long-grain and medium-grain cultivars, highlighting the unique response of each variety to drying conditions in the field. Similarly, Alwan-Alsharifi et al. (2017) noted that qualitative characteristics were influenced by the interaction of moisture content and machine parameters for specific cultivars. These findings underscore the complexity of the issue. Therefore, it is crucial to understand how these varietal differences in HRY response to harvest MC interact with different mechanical threshing conditions, especially for various cultivars grown in diverse agroecological and agronomic settings. This justifies the need to study the effect of threshing machine-crop parameters for different cultivars under different growing conditions.

Most previous studies in rice threshing with stationary mechanical threshers focuses on performance issues such as threshing capacity, threshing efficiency, threshing grain damage and losses (Ardeh and Gilandeh, 2008; Alizadeh and Khodabakhshipour, 2010; Naik et al., 2010; Olaye et al., 2016; Amponsah et al., 2017; Hailemesikel et al., 2024; Hailemesikel et al., 2025). Little studies have been conducted in investigating the effect of machine-crop parameters on HRY. These studies mainly focus on effects of harvest moisture content and cylinder speed on HRY. Nothing is reported on effects of other threshing parameters such as spike arrangement on HRY. Therefore, this study aimed to investigate the effects of grain moisture content, drum peripheral speed, and spike arrangement and their interactions on HRY for three locally grown rice varieties, taking into consideration the initial condition of the grain. The findings of this study will help determine machine-crop parameters with the utmost care for higher HRY and improve rice quality and quantity losses in sub-Saharan Africa.

2 Materials and methods

2.1 Experimental setup

A mechanical axial flow thresher was used to conduct the experiment. The thresher had an open threshing drum with ten evenly spaced threshing bars and the threshing concave were made from rectangular steel bar and steel wire as shown in Table 1. Details of the used thresher is depicted in Table 1.



a) threshing drum b) threshing concave

Figure 1 Threshing mechanism threshing drum threshing concave

Table 1 Specifications of the thresher

Parameters	Description
Drum diameter (mm)	300
Drum length (mm)	880
Number of threshing bars	10
Spike diameter (mm)	10
Spike length (mm)	80
Number of straw thrower blade	5
Concave clearance (mm)	20
Concave mesh size (L(mm) × W(mm))	18×28
Cleaning mechanism	*Oscillating sieve with blowing fan*
Oscillating stroke length (mm)	20
Blowing fan number of blade	4
Power source (kW)	10.5 kW diesel engine

The experiment was statistically designed as a complete randomized factorial design with four factors and three replicates. The three rice varieties used in the study were *Shaga*, *Ediget*, and *Nerica-4*, which are widely cultivated in the study area. The experiment involved three different harvest moisture contents, three thresher drum peripheral speeds, and three thresher spike arrangements. Details of experimental factors and levels are depicted in Table 2.

In the study area, it was common for farmers to use open sun field drying to dry the paddy to an average moisture content of approximately 11%-13% wet basis before the paddy is harvested. However, according to the current best practices, harvesting and threshing of rice has to be performed at about 22%-24% moisture content wet basis and followed by appropriate drying (e.g., sun drying or mechanical drying), for higher HRY (Butardo and Sreenivasulu, 2019). Based on these practices, three different harvest moisture contents were selected as a treatment in the range of 11% to 24% wet basis as depicted in Table 2.

The experimental drum speed for this experiment was determined based on previous studies (Dilday, 1989; Sharma et al., 1992; Ardeh and Gilandeh, 2008; Alizadeh and Khodabakhshipour, 2010; Naik et al., 2010; Olaye et al., 2016; Amponsah et al., 2017; Esgici et al., 2020; Hailemesikel et al., 2025) and by preliminary trials conducted under controlled threshing conditions. During these trials, various drum speeds were tested to assess the operational stability of the thresher, including feeding consistency, clogging tendency, and grain separation efficiency. It was observed that speeds below 700 rpm led to frequent clogging and poor separation, while speeds above 1050 rpm increased grain damage and caused excessive vibration. Based on these observations, three drum rotational speeds—720, 870, and 1020 rpm—were selected as optimal for further experimentation. Equation 1 commonly used in agricultural engineering to convert angular velocity to linear peripheral speed (Esgici et al., 2020; Yang et al., 2023), was applied to calculate the drum tip speed (m s^{-1}) for each *RPM* setting. The results are shown in Table 2.

$$v = r \times RPM \times \frac{2\pi}{60} \tag{1}$$

Where:

v=drum linear speed, m s^{-1};

r=drum radius, m.

RPM=angular speed in revolutions per minute.

In this experiment, three different spike arrangements based on spacing between spikes or number of spikes were employed. The spacing between each spike of 60 mm, 70 mm and 80 mm along the threshing bar with the number of spikes 120, 100, 80 respectively were considered as a treatment. This spike arrangements were selected based on locally available spike tooth type axial threshers.

The experiment was conducted at a constant feed rate of 600 kg h^{-1} biomass. This feed rate was established based on the highest possible threshing capacity and efficiency that can be achieved without clogging while threshing the highest moisture paddy (≈24%, wet basis) at lowest selected tip drum linear speed (17.3 m s^{-1}). Furthermore, less than 0.2% of unthreshed grain, most of them were immature, were observed at the specified conditions during preliminary test.

A control experiment was also conducted to distinguish pre-threshing damage from damage caused solely by the threshing operation. Manual threshing (hand rubbing) of rice was considered as a control experiment. Milling experiments were conducted to determine HRY and milling breakage using laboratory scale dehulling and milling machine.

Table 2 Details of experimental factors and levels

Experimental Variables	Levels (Designation)								
Variety	*'Shaga'* (VAR-1)			*'Ediget'* (VAR-2)			*'Nerica-4'* (VAR-3)		
MC (%) wet basis	24.01 (MC-1)	18.58 (MC-2)	12.42 (MC-3)	23.43 (MC-1)	17.95 (MC-2)	12.44 (MC-3)	23.80 (MC-1)	17.96 (MC-2)	11.44 (MC-3)
DS (m s^{-1})	17.3 (DS-1)	20.9 (DS-2)	24.6 (DS-3)	17.3 (DS-1)	20.9 (DS-2)	24.6 (DS-3)	17.3 (DS-1)	20.9 (DS-2)	24.6 (DS-3)
SS (mm) [spike number]	80 [80] (SS-1)	70 [100] (SS-2)	60 [120] (SS-3)	80 [80] (SS-1)	70 [100] (SS-2)	60 [120] (SS-3)	80 [80] (SS-1)	70 [100] (SS-2)	60 [120] (SS-3)

2.2 Grain dimensions and maximum breaking force of the rice grain

Paddy dimensions and brown rice bending strength for studied varieties were measured for randomly selected 100 paddy rice grains and the mean result is presented in Table 3. *Shaga* is the shortest grain in length. While *Nerica-4* is the longest, narrowest, and thinnest grain being studied, *Ediget* is the thickest and broadest. According to IRRI's classification of paddy rice length-width ratio, or grain shape, *Ediget* and *Shaga* are medium-grain varieties, while *Nerica-4* is a long-grain variety (Butardo and Sreenivasulu, 2019). The Stable Micro System food texture analyzer, model TA. XTplusC, was used to measure the maximum breaking force.

2.3 Experimental procedures

The three rice varieties under study were grown for test purpose in North-Western Ethiopia, Amhara region, Fogera district (11°55′N, 37°42′E, at an altitude of approximately 1828 meters above sea level), in the compound of Fogera National Rice Research and Training Center under rainfed condition in the period of July to October 2021. The rice varieties were planted with the manual hand transplanting method and hand weed management and other agronomical practices were applied according to the Fogera National Rice Research and Training Center (2020).

Table 3 Grain dimensions and maximum breaking force in bending

Variety	Length (mm)	Width (mm)	Thickness (mm)	Maximum breaking force (N)
Shaga	7.50±0.35	3.26±0.19	2.13±0.09	28.19±10.87
Ediget	8.59±0.32	3.59±0.21	2.28±0.10	26.85±11.54
Nerica-4	9.13±0.42	2.76±0.19	1.98±0.13	21.43±3.74

Once the rice reached maturity, it was harvested manually using sickles at three different moisture content levels as shown in Table 1, between October and December 2021. In order to avoid biases due to field variation and other uncontrolled source of variation, rice samples to be threshed were harvested for each test with completely randomized procedure. All randomizations were determined prior to testing by a lottery system randomization.

The moisture contents were measured using the oven dry method as described in Bhattacharya (2013) as well as the SATAKE MOISTEX digital grain moisture meter (model SS-8, measurement range 8.7%-40% and accuracy 0.5%) with three replications. The moisture content on wet basis, MC (%), was determined using Equation 2 for oven dried samples. Both approaches resulted in comparable results, with differences of less than 0.8%.

$$MC = \frac{W_w - D_w}{W_w} \times 100 \tag{2}$$

Where:

MC = moisture content wet basis, %;

Ww = weight of the sample before oven dry (wet weight), g;

Dw = weight of the sample after oven dry (dry weight), g.

The threshing experiment was conducted immediately after harvesting was finished on the same day, to minimize any other factor that might cause rice grain quality loss.

Threshing cylinders with three different spike arrangement were assembled turn by turn to conduct the experiment as designed. Cylinder rotational speeds were adjusted by changing the position of throttle control lever of the engine repeatedly until the required angular speed is achieved. The rotational drum speed (rpm) was measured using a Hioki Laser Tachometer (model FT3406, accuracy ±2%, measuring range 30-9999 rpm).

For each treatment combination, threshing experiment were conducted for 10 minutes with equal amounts of rice bundles at an average constant feed rate of 600 kg h^{-1} of fresh biomass, with three replicates.

After each experiment, a sample of 1kg were collected from the grain outlet of the thresher for laboratory analysis. The samples were sealed in a plastic bag and stored in a refrigerator at 4°C until milling experiment were performed.

Rice grains might be fissured in the field even before harvesting due to poor preharvest management and moisture adsorption. Therefore, to investigate and distinguish pre-threshing damage and grain damage solely attributed to threshing operation a control experiment is performed. In doing so, paddy rice is harvested with sickle manually and threshed by hand rubbing for each harvest moisture content with three replications for every studied variety. Threshing by hand rubbing assumed to cause no grain damage. Then a sample of 1kg were collected and sealed in a plastic bag and stored in a refrigerator at 4°C until milling experiment were performed.

2.4 Laboratory analysis

2.4.1 Milling Experiment

The samples of paddy rice were taken out of the refrigerator and dried in a room until the moisture content of the rough rice reaches 11.4%-12.5% wet basis for all samples, which is a typical moisture content of paddy for milling (Wazed et al., 2022). Then 200-gram paddy sample was de-hulled with a rubber roll de-husker (Model: Satake, THU-35 B, Japan) for each treatment combination with three replications.

Preliminary experimental runs were carried out to determine the approximate duration required to achieve the desired degree of milling. Brown rice samples were milled for each treatment combination using a laboratory-scale Satake abrasive milling machine (Model: TM05, Satake Corporation, Japan), operated at variable speeds (800–1,100 rpm) for 2 minutes. The machine accommodates 200 g samples and uses abrasive rollers (#30–#60 grit) to achieve controlled milling. Head rice and broken rice were separated manually. HRY (%) and milling breakage (%) were calculated using Equations 3 and 4, which are standard in rice milling quality studies (Rehal et al., 2017; Butardo and Sreenivasulu, 2019). To enhance the robustness of the analysis, future studies should also consider additional quality indicators such as degree of milling, chalkiness index, and whiteness index.

$$Head\ rice\ yield\ (\%) = \frac{Weight\ head\ rice}{Weight\ paddy\ sample} \times 100 \tag{3}$$

$$Milling\ breakage\ (\%) = \frac{Weight\ broken\ grain}{Weight\ paddy\ sample} \times 100 \tag{4}$$

2.5 Data analysis

The analysis of variance of general linear model (GLM), multivariate procedures were deployed using IBM SPSS statistical package software version 27 (IBM Corp., Armonk, NY, USA). Treatment means were considered significantly different if p-value, $p < 0.05$.

Regression analysis was employed to evaluate the effects of harvest MC, drum tip peripheral speed (DS), and spike spacing (SS) on HRY and milling breakage (MBR) across the three rice varieties. Prior to model fitting, interaction effects were tested using ANOVA, and although statistically significant, their sum of squares and F-ratio values were relatively small compared to the main effects. Therefore, to reduce model complexity and improve interpretability, interaction terms were excluded from the final regression models.

Multiple linear regression models were fitted using the ordinary least squares (OLS) method. Model selection was guided by the adjusted R^2 and mean squared error (MSE) criteria. All statistical analyses were conducted using IBM SPSS statistical package software version 27 (IBM Corp., Armonk, NY, USA). Significance was assessed at $p < 0.001$. The standardized beta coefficients and t-statistics were used to determine the relative influence of each predictor variable.

3 Results and discussion

Table 4 presents the ANOVA results for the effects of independent variables, namely VAR, MC, DS, and SS, and their interactions on HRY and milling breakage (MBR). The results indicated that effects of all the main effects (VAR, MC, DS, SS) and some of the interaction effects (VAR*MC, VAR*DS, MC*DS, MC*SS, DS*SS, VAR*MC*DS) on HRY and milling breakage are highly significant ($p < 0.01$).

Table 4 ANOVA results of effect of VAR, MC, DS, SS, and their interaction on HRY and milling breakage

Source	df	Dependent Variables			
		HRY		MBR	
		Mean Square	F	Mean Square	F
Corrected Model	80	117.75	862.23**	73.80	972.54**
Intercept	1	736088.45	5390054.37**	40396.19	532380.56**
VAR	2	2245.87	16445.51**	569.81	7509.46**
MC	2	2016.98	14769.45**	1986.77	26183.62**
DS	2	220.43	1614.08**	211.52	2787.66**
SS	2	34.26	250.86**	23.85	314.30**
VAR * MC	4	79.17	579.75**	64.61	851.44**
VAR * DS	4	2.37	17.34**	1.67	21.98**
VAR * SS	4	0.12	0.90^{ns}	0.34	4.50*
MC * DS	4	4.92	36.05**	5.00	65.95**
MC * SS	4	1.02	7.45**	0.69	9.09**
DS * SS	4	2.65	19.39**	1.36	17.93**
VAR * MC * DS	8	1.66	12.14**	1.71	22.51**
VAR * MC * SS	8	0.18	1.28^{ns}	0.35	4.61**
VAR * DS * SS	8	0.40	2.94*	0.17	2.25*
MC * DS * SS	8	0.40	2.92*	0.62	8.13**
VAR * MC * DS * SS	16	0.18	1.28^{ns}	0.14	1.84*
Error	162	0.14		0.08	
Total	243				
Corrected Total	242				

Note: ** Significant at p <0.01, *significant at p <0.05, ^{ns} not statistically significant.

3.1 Studied Variety Response on HRY and Milling Breakage

The least square (LS) mean percentage of HRY and milling breakage for experimental and control group is shown in Table 5. The LS mean result, showed that there is statistically significant difference among the varieties in HRY and milling breakage according to the LSD test (p <0.05).

The result indicated that, the variety *Shaga* which is the shortest grain, gives significantly higher HRY and lower milling breakage followed by *Ediget* and *Nerica-4* for both experimental and control group as shown in Table 5. On the other hand, *Nerica-4*, which is a long and slender grain variety, had lowest HRY and highest milling breakage. This can be attributed to the variation in kernel size, as longer, narrower, and thinner kernels are more susceptible to breakage due to abrasion during milling. Therefore, it is reasonable to expect that long grain rice varieties have lower HRY and higher milling breakage compared to shorter or medium grain varieties, as observed in prior studies (Goodman and Rao, 1985; Kalpanadevi et al., 2019; Xiao et al., 2023).

Table 5 LS mean HRY and MBR for studied varieties

Variety	Mean MBR (%)		Mean HRY (%)	
	Hand threshed	Axial thresher	Hand threshed	Axial thresher
Shaga	7.94^{a}	10.85^{a}	61.75^{a}	58.52^{a}
Ediget	9.08^{b}	11.93^{b}	60.72^{b}	57.62^{b}
Nerica-4	10.81^{c}	15.89^{c}	54.49^{c}	48.98^{c}

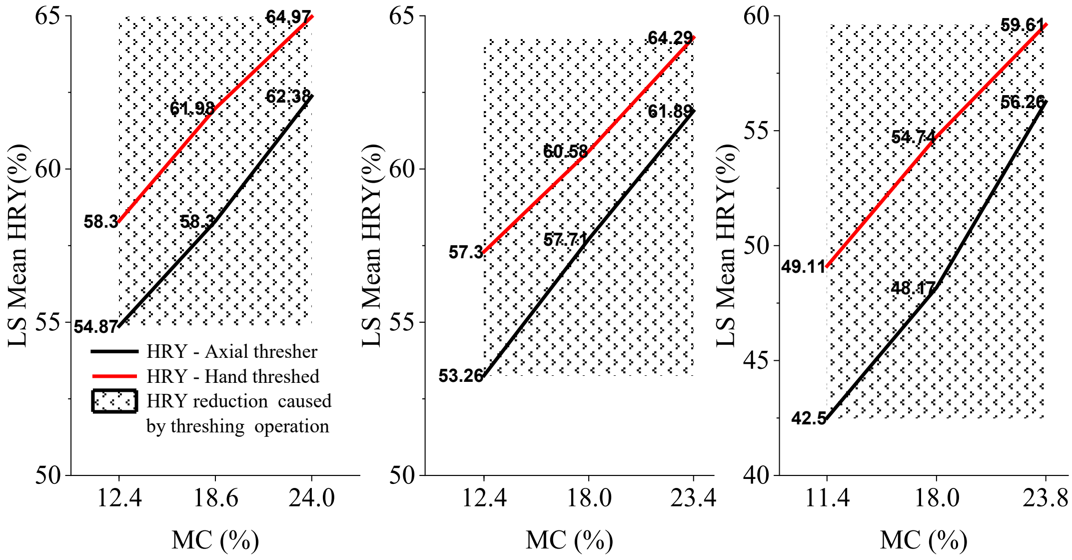
Note: $^{a-c}$ Means within the same column with the same letter superscript are not significantly different at p <0.05

Furthermore, there is a significant variation among varieties in average bending force to break brown rice as shown in Table 3. The lowest average breaking force in bending of 21.43N was recorded for *Nerica-4*. This could result in lower HRY, as it was previously reported by Lu and Siebenmorgen (1995) and more recent studies (Odek and Siebenmorgen, 2019; Li et al., 2022). The other reason for the difference in HRY could be because of the difference in physicochemical properties, such as grain hardness (Nassiri and Etesami, 2016; Kalpanadevi et al., 2019; Xiao et al., 2023), amylose content (Yadav and Jindal, 2008; Kalpanadevi et al., 2019; Yang et al., 2023; Pérez-almeida et al., 2025), and bran fat (Kalpanadevi et al., 2019; Yang et al., 2023; Liu et al., 2024), gel consistency (Yadav and Jindal, 2008; Devika et al., 2024).

3.2 Effect of moisture content on HRY and milling breakage

LS mean percentage of HRY and milling breakage for experimental and control groups, at various grain moisture contents is depicted in Figures 2 and 3. The result revealed that, that highest HRY and lowest milling breakage is observed at MC-1 (23.43%-24.01%). The findings also indicated that a decrease in moisture content resulted in a lower HRY and higher in milling breakage. These findings align with recent studies showing that rice harvested at higher moisture content yields better milling outcomes (Ilieva et al., 2014; Bhuiyan et al., 2024). A decrease in moisture content resulted in lower HRY and higher milling breakage, consistent with earlier findings (Dilday, 1989; Sharma et al., 1992; Andrews et al., 1993; Nalley et al., 2016). This could be due to rapid rewetting of paddy after the MC fell below the critical MC (15% or lower) (Siebenmorgen et al., 1992; Prakash et al., 2019; Mihretu, 2025). This leads to higher rate of fissuring which in turn resulted in higher rate of milling breakage and lower HRY.

In the present study it was assumed that HRY and milling breakage observed in hand threshed samples (control group) were not attributed to threshing operations. In other word, it was assumed that, threshing by hand rubbing could not cause damage to the grain. Therefore, the difference between the HRY and milling breakage observed in the samples threshed by the test thresher and those threshed manually represents the net contribution of the threshing operation to these factors. This net effect can be easily visualized as the shaded region in Figures 2 and 3, which display the net contribution of threshing operation on HRY and milling breakage, respectively.

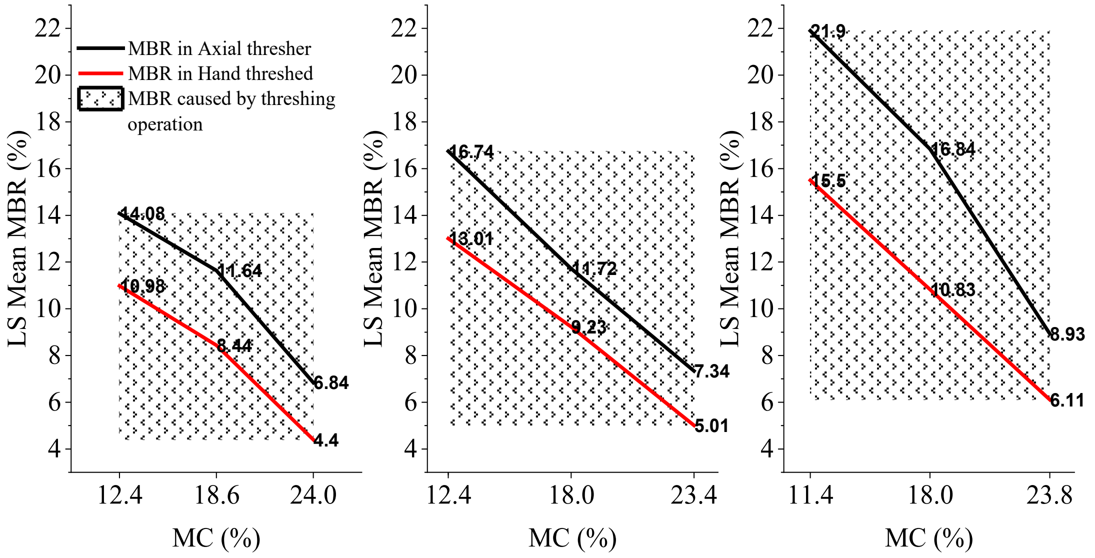


(a) *Shaga* (b) *Ediget* (c) *Nerica-4*

Figure 2 Effect of harvest moisture content on HRY

As it is depicted in Figure 2, the net mean effect of threshing operation on the decrement of HRY, which is the arithmetic difference between HRY of hand threshed and machine threshed samples, resulted in the range of 2.59% to 3.43% for *Shaga* and 2.4% to 4.04% for *Ediget* and 3.35% to 6.61% for *Nerica-4* as the harvest MC decreases from MC-1 (≈24%) to MC-3 (≈12%). With similar analogy the range of net milling breakage increment due to threshing operation would be 2.44% to 3.1% for *Shaga* and 2.33% to 3.73% for *Ediget* and 2.82% to 6.4% for *Nerica-4* as the harvest MC decreases from MC-1 (≈24%) to MC-3 (≈12%).

Furthermore, the result revealed that, the impact of the threshing operation on the decrement of HRY and increment of milling breakage increases with decreasing moisture content. This suggests that as moisture levels at harvest decrease, threshing becomes more damaging to the rice grains. Moreover, Figures 2 and 3 indicate that the *Nerica-4* variety is more severely affected by threshing operations than the other studied varieties. This could be due to the factors discussed in Section 3.1.



(a) *Shaga* (b) *Ediget* (c) *Nerica-4*

Figure 3 Effect of harvest moisture content on milling breakage

3.3 Effect of drum peripheral speed on HRY and milling breakage

Table 6 displays the LS mean percentage of HRY and milling breakage of the studied varieties at various drum peripheral speeds. The LS mean result indicated that, as the drum peripheral speed increased, HRY decreased and milling breakage increased significantly based on LSD (p <0.05) for all studied varieties.

Table 6 LS mean HRY (%) and MBR (%) at different DS

Variety	DS (m s^{-1})	HRY (%)	MBR (%)
	17.3	60.32^{a}	8.90^{a}
Shaga	20.9	58.29^{b}	11.01^{b}
	24.6	56.93^{c}	12.66^{c}
	17.3	59.53^{d}	10.37^{d}
Ediget	20.9	57.6^{e}	12.07^{e}
	24.6	55.74^{f}	13.55^{f}
	17.3	50.32^{g}	14.44^{g}
Nerica-4	20.9	49.01^{h}	15.85^{h}
	24.6	47.61^{i}	17.39^{i}

Note: $^{a\text{-}i}$ Means within the same column with the same letter superscript are not significantly different at p <0.05

As shown in Table 6, as the drum peripheral speed increased from 17.3 to 24.6 m s^{-1} the LS mean HRY decreased from 60.32% to 56.93% for *Shaga*, 59.53% to 55.74% for *Ediget* and 52.7 to 49.99% for *Nerica-4*. In contrast, the LS mean milling breakage increased from 8.9% to 12.66% for *Shaga*, 9.54% to 12.52% for *Ediget*, and 15.44% to 18.39% for *Nerica-4*. This can be attributed to the fact that higher drum peripheral speed leads to a greater impact force on the rice kernels and can cause the grains to be thrown and collide with the drum and concave walls, resulting in damage. As a result, higher drum peripheral speed results in lower HRY and higher milling breakage. These findings are consistent with previous studies that demonstrate a negative correlation between drum tip speed and HRY, and a positive correlation with milling breakage (Dilday, 1989; Esgici et al., 2020).

3.4 Effect of spike spacing on HRY and milling breakage

Table 7 showed the LS mean percentage of HRY and milling breakage for the studied varieties at different spike spacings. The results indicated a decrease in HRY and an increase in milling breakage as the spacing between the spikes decreased or the number of spikes per unit surface area of the drum increased. Specifically, as the spike spacing decreased from 80 mm to 60 mm, the LS mean percentage of HRY decreased from 59.12% to 57.86% for *Shaga*, 58.33% to 56.88% for *Ediget*, and 51.93% to 50.74% for *Nerica-4*. In contrast, the LS mean milling breakage increased from 10.19% to 11.50% for *Shaga*, 10.65% to 11.52% for *Ediget*, and 16.37% to 17.45% for *Nerica-4*. This could be because as the number of spikes increases, the grains are hit more frequently by the spikes, leading to a higher percentage of fissured and broken grains, that could result in lower HRY.

Table 7 LS mean HRY (%) and MBR (%) at different SS

Variety	SS (mm)	HRY (%)	MBR (%)
	80	59.12^{a}	10.19^{a}
Shaga	70	58.57^{b}	10.88^{b}
	60	57.86^{c}	11.50^{c}
	80	58.33^{d}	11.48^{c}
Ediget	70	57.65^{e}	11.97^{d}
	60	56.88^{f}	12.35^{e}
	80	49.55^{g}	15.37^{f}
Nerica-4	70	49.03^{h}	15.87^{g}
	60	48.36^{i}	16.44^{h}

Note: $^{a\text{-}h}$ Means within the same column with the same letter superscript are not significantly different at $p < 0.05$

3.5 Effect of the independent variables interaction on HRY and milling breakage

Tables 8 and 9 present the mean interaction effect of the independent variables on HRY and milling breakage. The results showed that *Nerica-4* variety had the lowest HRY and highest milling breakage at the lowest moisture content (MC-3), highest drum speed (DS-3), and shortest spike spacing (SS-3). In contrast the highest HRY and lowest milling breakage was recorded for *Shaga* variety at highest moisture content (MC-1), lowest drum peripheral speed (DS-1) and widest spike spacing (SS-1).

Table 8 Mean HRY (%) for interaction VAR*MC*DS*SS

	Variety	MC (%)	DS (m s^{-1}) X SS (mm									LS Mean
			17.3			20.9			24.6			
			80	70	60	80	70	60	80	70	60	
VAR XMC		24.01	63.9	63.1	62.9	62.7	62.3	62.1	62.3	61.4	60.6	62.4^{a}
	Shaga	18.58	60.8	60.8	60.3	58.5	58.0	57.2	57.5	56.4	55.2	58.3^{b}
		12.42	57.0	57.2	56.8	55.2	54.8	53.8	54.1	53.2	51.6	54.9^{c}
		23.43	63.3	63.2	62.9	62.7	61.7	61.6	60.9	60.5	60.2	61.9^{d}
	Ediget	17.95	60.0	59.7	59.4	58.3	57.7	56.8	57.3	55.9	54.4	57.7^{e}
		12.44	56.0	55.9	55.4	54.1	53.3	52.3	52.4	51.0	49.0	53.3^{f}
		23.80	58.1	57.4	57.2	56.8	56.3	55.8	55.3	55.0	54.5	56.3^{g}
	Nerica-4	17.96	49.9	49.7	49.0	49.1	48.5	47.9	47.6	46.5	45.5	48.2^{h}
		11.44	44.6	43.9	43.2	42.7	42.6	41.5	41.9	41.4	40.7	42.5^{i}
		LS Mean	57.1	56.8	56.3	55.6	55.0	54.3	54.4	53.5	52.4	55.0

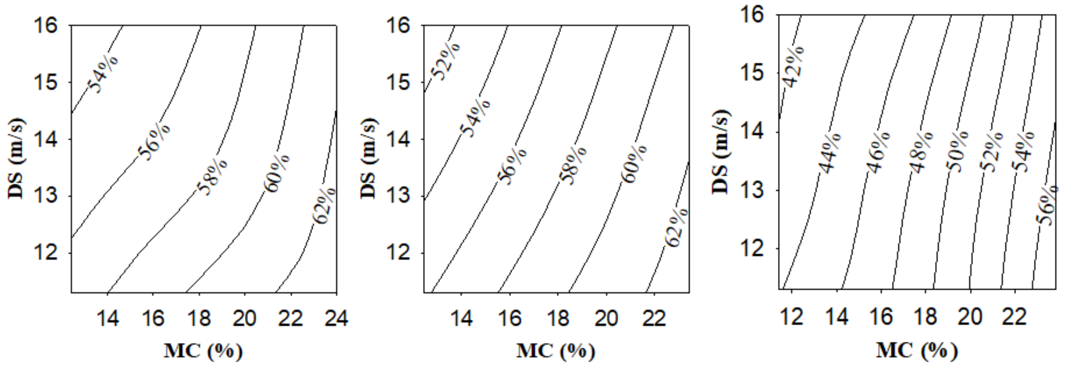
Note: $^{a-i}$ Means within the same column with the same letter superscript are not significantly different at $p < 0.05$

Table 9 Mean MBR (%) of interaction of VAR*MC*DS*SS

	Variety	MC (%)	DS (m s^{-1}) X SS (mm)									
			17.3			20.9			24.6			
			80	70	60	80	70	60	80	70	60	**LS Mean**
VAR XMC		24.01	4.76	5.66	5.9	6.12	7.16	6.91	8	8.5	8.52	6.8^{a}
	Shaga	18.58	8.88	9.1	9.7	11.3	11.9	12.8	12.4	14	15	11.6^{b}
		12.42	11.9	11.8	12	13.8	14.3	14.9	14.6	16	17.4	14.1^{c}
		23.43	6.37	7	6.8	7	7.3	7.44	7.7	8	8.41	7.3^{d}
	Ediget	17.95	9.86	9.93	10	11.8	11.9	12	12.4	14	14.1	11.7^{b}
		12.44	14.2	14.4	15	16.3	17.2	17.8	17.7	19	19.8	16.7^{e}
		23.80	6.86	7.81	8	8.41	8.98	9.45	9.91	10	10.8	8.9^{f}
	Nerica-4	17.96	14.8	15.1	16	16.1	16.4	16.9	17.7	19	19.8	16.8^{e}
		11.44	20	20.4	21	21.9	22	22.6	22.6	23	23.6	21.9^{g}
		LS Mean	10.8	11.3	11.6	12.5	13.0	13.4	13.7	14.4	15.3	12.9

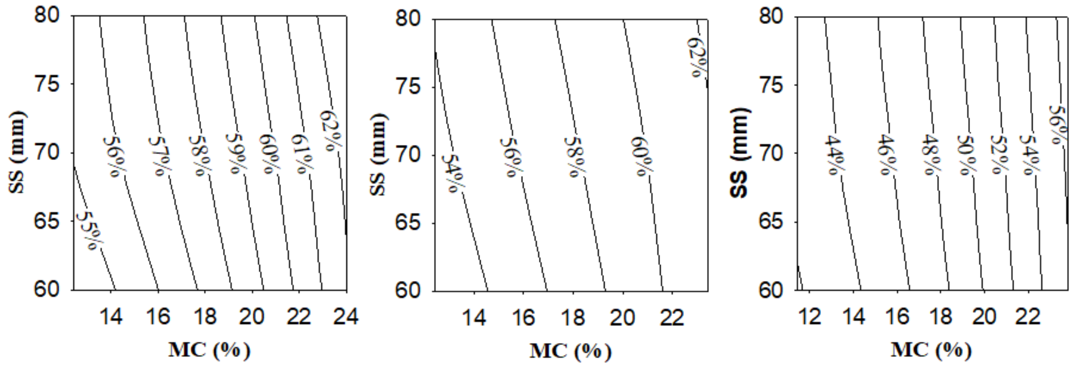
Note: $^{a-g}$ Means within the same column with the same letter superscript are not significantly different at $p < 0.05$

Two-way contour plots were used to scrutinize the relationship between each of the independent variables (MC, DS, and SS) and their effect on HRY and milling breakage for all studied varieties. The contours represent HRY in Figures 4, 5 and 6 and milling breakage in Figures 7, 8 and 9. As it is depicted in Figures 4 and 7 MC and DS are negatively interacted, that means higher MC and lower DS more likely to produce higher HRY and lower milling breakage and vice versa. The plots also indicate that the effect of MC is stronger than that of DS. Figures 5 and 8 showed that a positive interaction between MC and SS, with higher MC and wider SS that resulted in higher HRY and lower milling breakage and vice versa. The plots clearly reveals that the effect of SS is very weak than that of MC. Furthermore, as it is depicted in Figures 6 and 9 SS and DS are negatively interacted, that means larger SS and lower DS leading to higher HRY and lower milling breakage and vice versa. The plots also indicate that the effect of DS is stronger than that of SS.



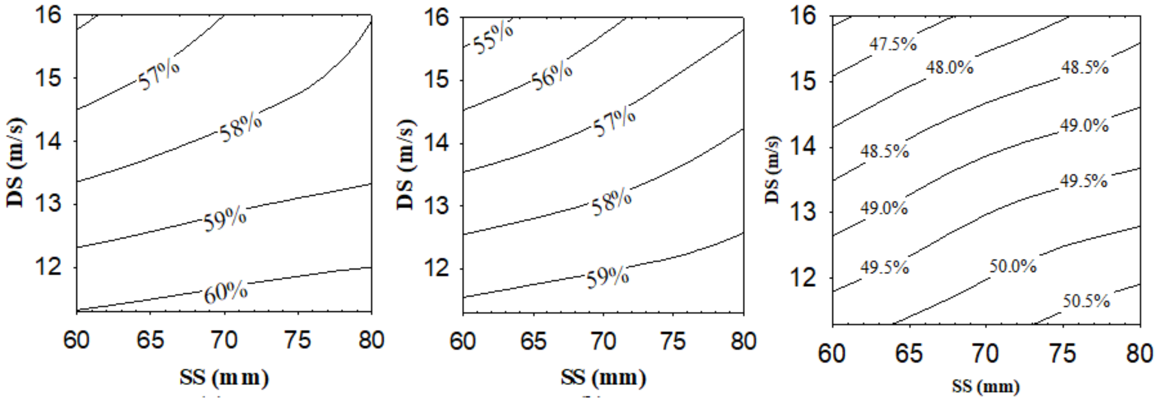
(a) *Shaga* (b) *Ediget* (c) *Nerica-4*

Figure 4 Two-way Contour Plots: Interaction effects of MC*DS on HRY



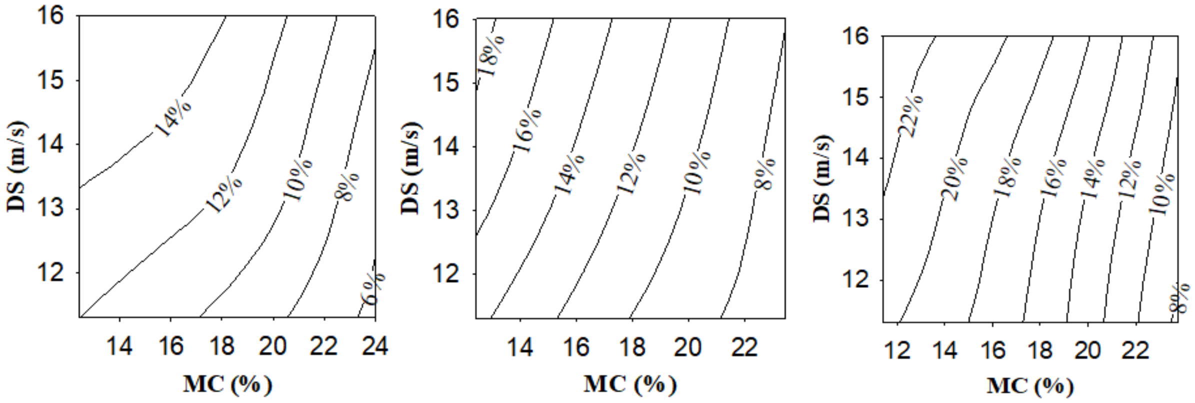
(a) *Shaga* (b) *Ediget* (c) *Nerica-4*

Figure 5 Two-way Contour Plots: Interaction effects of MC*SS on HRY



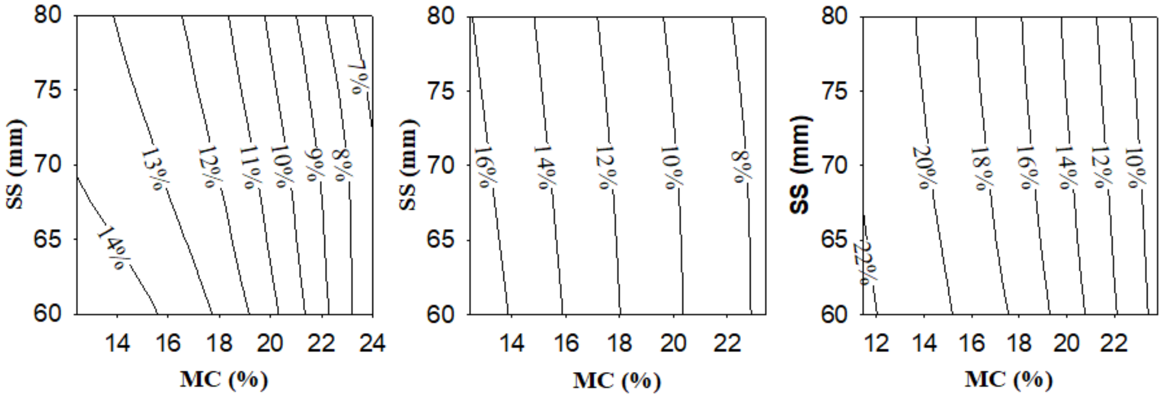
(a) *Shaga* (b) *Ediget* (c) *Nerica-4*

Figure 6 Two-way Contour Plots: Interaction effects of DS*SS on HRY



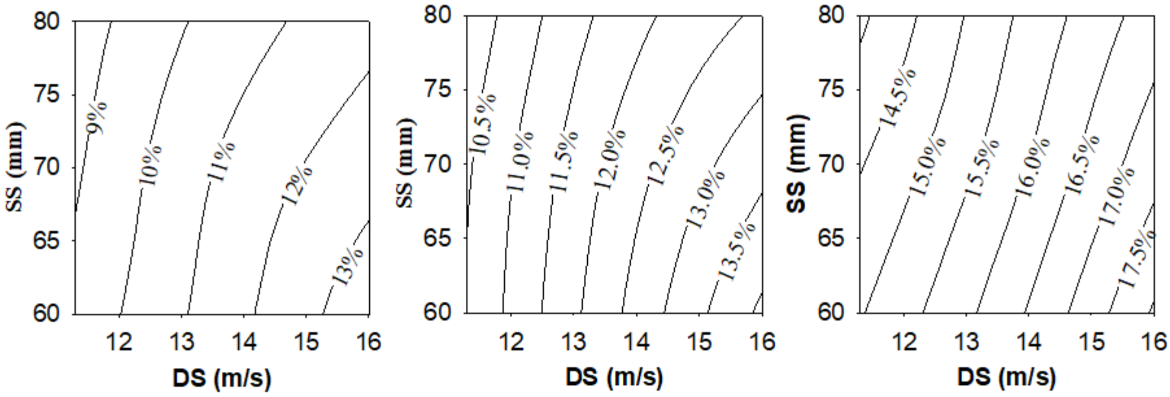
(a) *Shaga* (b) *Ediget* (c) *Nerica-4*

Figure 7 Two-way Contour Plots: Interaction effects of MC*DS on MBR



(a) *Shaga* (b) *Ediget* (c) *Nerica-4*

Figure 8 Two-way Contour Plots: Interaction effects of MC*SS on MBR



(a) *Shaga* (b) *Ediget* (c) *Nerica-4*

Figure 9 Two-way Contour Plots: Interaction effects of DS*SS on MBR

3.6 Regression analysis

The sum of squares and the F-ratio values are quite small for interaction effects in comparison to the main effects, despite the fact that the interaction effects are significant. This suggests that the variability resulting from interaction effects is less important or can be captured by the group mean. As a result, regression models were fitted using the adjusted R2 and MSE criterion, by omitting the interaction effect to reduce the complexity of the model. Therefore, the prediction variables of harvest MC (%), DS (m s^{-1}), and SS (mm), were used to regress the dependent variables of HRY and milling breakage.

The independent variables significantly predict HRY and milling breakage for all studied varieties, at $p < 0.001$, as shown in Table 10 and Table 11. The R^2 values indicated that the models accounted for 95.5%, 97.1%, and 98.0% of the variance in HRY, and 93.3%, 97.6%, and 97.4% of the variance in milling breakage for the *Shaga*, *Ediget*, and *Nerica-4* varieties, respectively.

The regression coefficients of the independent variables indicated that harvest moisture content and spike spacing positively influenced HRY, while negatively influencing milling breakage for all the studied varieties. Conversely, drum peripheral speed negatively influenced HRY, while positively influencing milling breakage for all the studied varieties, as shown in Table 10 and Table 11.

Table 10 Regression results of HRY (%) under different threshing conditions

Model	*Shaga*				*Ediget*				*Nerica-4*			
	B	Beta	t	Sig.	B	Beta	t	Sig.	B	Beta	t	Sig.
(Constant)	51.94		52.30	.000	49.35		54.55	.000	32.95		30.55	.000
MC (%)	0.65	0.88	36.29	.000	0.78	0.89	46.02	.000	1.11	0.97	60.54	.000
DS (m sec^{-1})	-0.46	-0.40	-16.39	.000	-0.52	-0.39	-20.22	.000	-0.37	-0.19	-11.98	.000
SS (mm)	0.06	0.15	6.13	.000	0.07	0.15	7.70	.000	0.06	0.08	5.23	.000
F(3,77)		541.07		.000		862.15		.000		1278.80		.000
R^2		0.955				0.971				0.980		

Table 11 Regression results of milling breakage (%) under different threshing conditions

Model	*Shaga*				*Ediget*				*Nerica-4*			
	B	Beta	t	Sig.	B	Beta	t	Sig.	B	Beta	t	Sig.
(Constant)	16.01		13.28	.000	21.78		25.67	.000	29.73		25.02	.000
MC (%)	-0.62	-0.84	-28.67	.000	-0.86	-0.94	-53.45	.000	-1.04	-0.96	-51.76	.000
DS (m sec^{-1})	0.51	0.44	15.00	.000	0.41	0.30	16.94	.000	0.40	0.22	11.82	.000
SS (mm)	-0.07	-0.15	-5.22	.000	-0.04	-0.09	-4.95	.000	-0.05	-0.08	-4.32	.000
F(3,77)		358.01		.000		1055.98		.000		945.93		.000
R^2		0.933				0.976				0.974		

Equations 5, 6, and 7 illustrate the regression equations for the HRY of the *Shaga (HRY_S), Ediget (HRY_E)*, and *Nerica-4 (HRY_N)* varieties, respectively. Equations 8, 9, and 10 illustrate the regression equations for the milling breakage (MBR) of *Shaga (MBR_S), Ediget (MBR_E)*, and *Nerica-4 (MBR_N)* varieties, respectively.

$$HRY_S\,(\%) = 51.943 + (0.646 \times MC\,(\%)) - (0.464 \times DS\,(m/s)) + (0.0633 \times SS\,(mm)) \quad (5)$$

$$HRY_E\,(\%) = 49.354 + (0.785 \times MC\,(\%)) - (0.519 \times DS\,(m/s)) + (0.0722 \times SS\,(mm)) \quad (6)$$

$$HRY_N\,(\%) = 32.950 + (1.109 \times MC\,(\%)) - (0.372 \times DS\,(m/s)) + (0.059 \times SS\,(mm)) \quad (7)$$

$$MBR_S\,(\%) = 16.008 - (0.619 \times MC\,(\%)) + (0.515 \times DS\,(m/s)) - (0.0653 \times SS\,(mm)) \quad (8)$$

$$MBR_E(\%) = 21.776 - (0.855 \times MC\,(\%)) + (0.408 \times DS\,(m/s)) - (0.043 \times SS\,(mm)) \quad (9)$$

$$MBR_N\,(\%) = 29.727 - (1.044 \times MC\,(\%)) + (0.404 \times DS\,(m/s)) - (0.054 \times SS\,(mm)) \quad (10)$$

The influence of each variable on HRY and milling breakage for all studied varieties, are indicated by standardized beta coefficients and t statistic in Table 10 and Table 11. Results indicated that harvest moisture content, with the highest beta coefficient and t-statistic, was the most influential factor affecting HRY and milling breakage for all the studied varieties, followed by drum peripheral speed and spike spacing.

4 Conclusion

This study examined the impact of different factors on HRY and milling breakage in three rice varieties, *Shaga*, *Ediget*, and *Nerica-4*. The results indicated that all the main effects and some of the interaction effects of the independent variables, including variety, harvest moisture content, drum peripheral speed, and spike spacing, significantly impacted HRY and milling breakage. *Shaga* variety (the shortest variety under study) had higher HRY and lower milling breakage, whereas *Nerica-4* (the longest variety under study) had lower HRY, and higher milling breakage compared to the other two varieties. The impact of harvest moisture content was greater than the other factors, as MC increased HRY increased and milling breakage decreased. Furthermore, the result revealed that, as moisture content levels at harvest decrease, mechanical threshing becomes more damaging to the rice grains. As the drum peripheral speed increased, HRY decreased and milling breakage increased significantly for all studied varieties. Decreasing the spike spacing or increasing the number of spikes per unit surface area of the drum negatively impacted HRY and positively impacted milling breakage. Regression analysis of the data indicated that the harvest moisture content was the most critical factor affecting HRY and milling breakage percentage, followed by the drum peripheral speed and spike spacing. These findings can be used to develop effective strategies to minimize rice grain damage during rice milling.

References

Alizadeh, M. R., and M. Khodabakhshipour. 2010. Effect of threshing drum speed and crop moisture content on the paddy grain damage in axial-flow thresher. *Cercetari Agronomice in Moldova*, 434(144): 5–11

Alwan-Alsharifi, S. K., A. Arabhosseini, M. H. Kianmehr, and A. M. Kermani. 2017. Effect of moisture content, clearance and machine type on some qualitative characteristics of rice (Tarm hashemi) cultivar. *Bulgarian Journal of Agricultural Science*, 23(2): 348–355.

Amponsah, S. K., A. Addo, K. Dzisi, J. Moreira, and S. A. Ndindeng. 2017. Comparative evaluation of mechanised and manual threshing options for Amankwatia and AGRA rice varieties in Ghana. *Journal of Agricultural Engineering*, 48(4): 181–189.

Andrews, S. B., T. J. Siebenmorgen, E. D. Vories, D. H. Loewer, and A. Mauromoustakos. 1993. Effects of combine operating parameters on harvest loss and quality in rice. *Transactions of the ASAE*, 36(6): 1599–1607.

Ardeh, E. A. A., and Y. A. Gilandeh. 2008. Investigation of the effective factors on threshing loss, damaged grains percent and material other than grain to grain ratio on an auto head feed threshing Unit. *American Journal of Agricultural and Biological Sciences*, 3(4): 699–705.

Arouna, A., I. A. Fatognon, K. Saito, and K. Futakuchi. 2021. Moving toward rice self-sufficiency in sub-Saharan Africa by 2030: Lessons learned from 10 years of the Coalition for African Rice Development. *World Development Perspectives*, 21: 100291.

Berrio, L. E., and F. E. Cuevas-Perez. 1989. Cultivar differences in milling yields under delayed harvesting of rice. *Crop Science*, 29(6): 1510–1512.

Bhattacharya, K. R. 2013. *Rice Quality: A Guide to Rice Properties and Analysis*. Cambridge, UK: Woodhead Publishing Limited.

Bhuiyan, G. K., M. Ahmmed, S. Paul, D. Huda, M. A. Hossain, A. Rahman, and B. Nath. 2024. Milling recovery of BRRI dhan71 and BRRI dhan82 under different moisture content. *Journal of Agricultural Machinery and Bioresources Engineering*, 8(2): 62–67.

Butardo, V. M., and N. Sreenivasulu. 2019. Improving head rice yield and milling quality: State-of- the-art and future prospects. In *Rice Grain Quality: Methods and Protocols*, ed. N. Sreenivasulu, ch. 1, 1–18. New York: Springer Science+Business Media, LLC.

Devika, S., A. Anand, A. Elangovan, K. S. Pavithra, and R. Ramesh. 2024. Physiochemical characterization of rice genotypes based on gel consistency and alkali digestion under different N levels. *International Journal of Research in Agronomy*, 7(6): 341–344.

Dilday, R. H., 1989. Milling quality of rice: Cylinder speed vs. grain-moisture content at harvest. *Crop Science*, 29(6): 1532–1535.

Esgici, R., F. G. Pekitkan, and A. Sessiz. 2020. Evaluation of cylinder rotational speed for rice grain losses and broken grain ratio. *Journal of Agricultural Machinery*

Science, 16(2): 28–33.

FAO. 2023. FAOSTAT. Available at: https://www.fao.org/faostat/en/#home. Accessed 10 September 2024).

Feliz, D. J., A. Proctor, M. A. Monsoor, and R. L. Eason. 2005. The effects of damage kernel caused by combine harvester settngs on milled rice free fatty acid levels. *Journal of Food Science*, 70(6): 376–379.

Fogera National Rice Research and Training Center. 2020. Rice production agronomic recommendation guideline. Woreta, Ethiopia: Fogera National Rice Research and Training Center

Goodman, D. E., & Rao, R. M. 1985. Effect of Grain Type and Milled Rice Kernel Hardness on the Head Rice Yields. *Journal of Food Science*, *50*(3), 840–840. https://doi.org/10.1111/j.1365-2621.1985.tb13811.x

Hailemesikel, S. T., M. Alebachew, M. A. Delele, A. N. Ali, S. W. Fanta, and G. Kidanemariam. 2025. Effects of crop parameters and feed rates on performances of axial rice thresher. In *Sustainable Development Research in Manufacturing, Process Engineering, Green Infrastructure, and Water Resources: Advancement of Science and Technology*, eds. S. W. Fanta, M. W. Tenagashaw, M. T. Tigabu, and E. Y. Gedilu, ch. 7, 111–124. Switzerland: Springer Nature.

Hailemesikel, S. T., M. Alebachew, M. A. Delele, A. N. Ali, S. Workneh Fanta, and G. Kidanemariam 2024. Effects of machine-crop parameters on mechanical grain damage in rice threshing. *Cogent Food and Agriculture*, 10(1): 2367381.

Ilieva, V., I. Karov, L. Mihajlov, N. M. Ruzdik, and M. Ilievski. 2014. Effect of rice moisture at harvest and rough rice storage time on milling yield and grain breakage. In *International Scientific Conference Breeding and Techologies Field Crops*, 19-24. Karnobat, Bulgaria, June 19-20, 2014 .

Kalpanadevi, C., V. Singh, and R. Subramanian. 2019. Impact of physicochemical properties on duration and head rice yield during abrasive and friction milling of rice. *Journal of Food Science and Technology*, 56(8): 3900–3909.

Kebede, L., B. Getnet, Y. Lema, M. Alebachew, and M. Ageze. 2019. Post-harvest processes and advances to introduce loss- reducing technologies for rice. In *Advances in Rice Research and Development in Ethiopia*, eds. T. Tadesse, M. Atnaf, D. Alemu, T. Tadesse, and K. Shiratori, ch. 14, 184–197. Addis Ababa, Ethiopian: Ethiopian Institute of Agricultural Research.

Li, Y., Y. Chen, Q. Ding, R. He, and W. Ding. 2022. Analysis of relationship between head rice yield and breaking force of Japonica rice grains at different maturity stages. *International Agrophysics*, 36: 1–11.

Liu, X., Z. Shi, Y. Zhang, H. Li, H. Pei, and H. Yang. 2024. Characteristics of damage to brown rice kernels under single and continuous mechanical compression conditions. *Foods*, 13(7): 1069.

Lu, R., & Siebenmorgen, T. J. 1995. Correlation of Head Rice Yield to Selected Physical and Mechanical Properties of Rice Kernels. *Transactions of the ASAE*, *38*(3), 889–894. https://doi.org/10.13031/2013.27905

Manful, J. 2010. Developing rice varieties with high grain quality in Africa : Challenges and prospects. In *Proc. of the Second Africa Rice Congress*, 1.20.1-1.20.3. Bamako, Mali, 22-26 March.

Mihretu, M. A. 2025. Key factors affecting the quality of milling recovery in rice processing. *American Journal of Mechanical and Industrial Engineering*, 10(1): 29–39.

Musa, M. H., J. K. Agomuo, M. A. Dandago, K. S. Atanda, D. Nahemiah, and A. Terpase. 2024. Paddy rice (oryza sativum) production and processing in nigeria: A Review. *Dutse Journal of Pure and Applied Sciences*, 10(1b): 282–292.

Nahemiah, D., I. Nkama, I. Paul Yahaya, M. Halidu Badau, and A. Umar. 2021. Advances in rice postharvest loss reduction strategies in Africa through low grade broken rice fractions and husk value addition. In *Recent Advances in Rice Research*, ed. M. R. Ansari, ch. 11, 207–226. London, UK: IntechOpen.

Naik, R. K., S. Patel, A. K. Verma, and A. K. Shrivastava. 2010. Effect of crop and machine parameters on performance of baddy thresher. *Agricultural Engineering Today*, 34(1): 30–32.

Nalley, L., B. Dixon, J. Tack, A. Barkley, and K. Jagadish. 2016. Optimal harvest moisture content for maximizing mid-south rice milling yields and returns. *Agronomy Journal*, 108(2): 701–712.

Nassiri, S. M., and S. M. Etesami. 2016. Estimation of head rice yield by measuring the bending strength of kernels after drying by different drying methods. *CIGR Journal*, 18(2): 368–377.

Ndindeng, S. A., A. Candia, D. L. Mapiemfu, V. Rakotomalala, N. Danbaba, K. Kulwa, P. Houssou, S. Mohammed, O. M. Jarju, S. S. Coulibaly, E. A. Baidoo, J. Moreira, and K. Futakuchi. 2021. Valuation of rice postharvest losses in Sub-Saharan Africa and its mitigation strategies. *Rice Science*, 28(3): 212–216.

Odek, Z. R., and T. J. Siebenmorgen. 2019. Estimating head rice yield of long-grain rice using a bending force instrument. *Applied Engineering in Agriculture*, 35(3): 319–323.

Olaye, A. R. I. B., J. Moreira, S. K. Amponsah, S. Okurut, and D. J. Hounhouigan. 2016. Effect of threshing drum speed and crop weight on paddy grain quality in axial-flow thresher (ASI). *Journal of Multidisciplinary Engineering Science and Technology*, 3(1): 3716–3721.

Pérez-almeida, I., O. Navia-pesantes, and R. Celi-herán. 2025. Assessment of rice amylose content and grain quality through marker-assisted selection. *International Journal of Plant Biology*, 16(2): 52.

Prakash, B., T. J. Siebenmorgen, K. E. Gibson, and S. Kumari. 2019. Effect of storage moisture content on milling characteristics of rough rice. *Transactions of the ASABE*, 62(4): 1011–1019.

Rehal, J., G. J. Kaur, and A. K. Singh. 2017. Influence of milling parameters on head rice recovery : A Review. *International Journal of Current Microbiology and Applied Sciences (IJCMAS)*, 6(10): 1278–1295.

Saito, K., K. Senthilkumar, E. R. Dossou-Yovo, I. Ali, J. M. Johnson, G. Mujawamariya, and J. Rodenburg. 2023. Status quo and challenges of rice production in sub-Saharan Africa. *Plant Production Science*, 26(3): 320–333.

Seck, P. A., A. Diagne, S. Mohanty, and M. C. S. Wopereis. 2012. Crops that feed the world 7: Rice. *Food Security*, 4(1): 7–24.

Sharma, A. D., O. R. Kunze, and N. N. Sarker. 1992. Impact damage on rough rice. *Transactions of the American Society of Agricultural Engineers*, 35(6): 1929–1934.

Siebenmorgen, T. J., P. A. Counce, R. Lu, and M. F. Kocher. 1992. Correlation of head rice yield with individual kernel moisture content distribution at harvest. *Transactions of the ASAE*, 35(6): 1879–1884.

Siebenmorgen, T. J., R. C. Bautista, and P. A. Counce. 2007. Optimal harvest moisture contents for maximizing milling quality of long- and medium-grain rice cultivars. *Applied Engineering in Agriculture*, 23(4): 517–527.

Thompson, J. F., & Mutters, R. G. 2006. Effect of Weather and Rice Moisture at Harvest on Milling Quality of California Medium-Grain Rice. Transactions of the ASABE, 49(2), 435–440.

USDA. 2009. United States Standards For Rice. Washington, D.C.: USDA.

Wazed, M. A., N. H. M. Mozumder, and M. S. H. Sarker. 2022. Head rice yield of paddy dried in two stage and conventional drying methods. *CIGR Journal*, 24(3): 190–200.

Xiao, X., L. Yang, Z. Wang, Y. Luo, B. Cui, S. Song, Y. Zhang, and H. Pei. 2023. Multi-dimensional research on brown rice fracture characteristics and mechanism under quasi-static compression. *Journal of Cereal Science*, 114: 103803.

Yadav, B. K., and V. K. Jindal. 2008. Changes in head rice yield and whiteness during milling of rough rice (*Oryza sativa* L .). *Journal of Food Engineering*, 86(1): 113–121.

Yang, L., Y. Luo, X. Xiao, Y. Li, J. Zhao, H. Pei, S. Song, and Y. Zhang. 2023. Research on rice grain damage behavior with experimental and finite element modeling. *Journal of Food Process Engineering*, 46(8): e14369.

Yuan, S., K. Saito, P. A. J. van Oort, M. K. van Ittersum, S. Peng, and P. Grassini. 2024. Intensifying rice production to reduce imports and land conversion in Africa. *Nature Communications*, 15(1): 835.

Zenna, N., K. Senthilkumar, and M. Sie. 2017. Rice Production in Africa. In *Rice Production Worldwide*, eds. B. S. Chauhan, K. Jabran, and G. Mahajan, ch. 5, 117–136. Switzerland: Springer Nature.