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EVALUATION OF MORPHOLOGICAL AND PHYSICAL CHARACTERISTICS OF RANJIT SUB-1 RICE FOR MECHANIZED HARVESTING IN ASSAM, INDIA

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ABSTRACT

This study characterized harvest-stage properties of Ranjit Sub-1 rice using 25 field records and descriptively evaluated harvesting performance across three grain moisture levels and four forward speeds, with three independent runs per combination. Mean plant height, stem diameter and hill diameter were 1292.01 ± 63.22, 6.39 ± 0.72 and 66.60 ± 8.73 mm, respectively. Productive stems per hill showed greater variability than plant height (CV: 24.26% versus 4.89%). Grain and straw moisture averaged 21.98 ± 1.43% and 40.34 ± 4.09% wet basis. Across grain moisture levels of 19.78–23.44%, mean hourly fuel consumption increased from 13.80 to 15.46 L h^{-1}, while the active harvesting capacity ratio decreased from 68.02% to 50.30%. These descriptive findings provide crop-specific testing conditions but do not establish statistically significant treatment effects, overall field efficiency, improved fuel-use efficiency or environmental benefits.

Key words : Ranjit Sub-1, Paddy, Crop geometry, Stand structure, Moisture content, Mechanized harvesting.

Introduction

Mechanized rice harvesting requires coordinated cutting, gathering, conveying, threshing and cleaning operations, each of which interacts with a crop that varies in geometry, spatial arrangement and material condition. Consequently, harvesting performance depends on both machine configuration and the characteristics of the crop presented to the mechanism. Field investigations have shown that combine harvesting efficiency varies with field size and crop conditions, including lodging, while studies of grain breakage monitoring demonstrate the importance of evaluating product damage during machine operation (Xangsayasane *et al*., 2019; Chen *et al*., 2020; Dwivedi *et al*., 2025; Komatineni *et al*., 2024; Komatineni *et al*., 2025). These findings establish the need to characterize the target crop before translating machinery specifications into operating recommendations. For cultivar-specific harvesting applications, measurements of plant architecture, stem geometry, stand structure and moisture condition provide the initial evidence needed to define representative testing conditions.

Plant architecture determines the position and arrangement of the material encountered by a harvesting system. Plant height describes the overall vertical extent of the crop, whereas panicle position and dimensions characterize the distribution of the grain-bearing structures. Basal stem geometry provides additional information relevant to cutting and structural support. Research on high-yielding rice populations has demonstrated that lodging resistance depends on the configuration of internodes and stem stiffness, together with plant height (Zhang *et al*., 2014). Similarly, comparisons of machine-transplanted rice varieties have identified differences in lodging behaviour associated with plant type, stem geometry and dry-matter redistribution (Ding *et al*., 2021). Kashiwagi *et al*. (2008) further

demonstrated the contribution of stem diameter to pushing resistance, while showing that associated changes in plant height must also be considered. Collectively, these studies support measuring architectural traits together, because the engineering significance of an individual dimension depends on its relationship with the rest of the plant.

Stem diameter is particularly relevant to the characterization of material entering a cutting mechanism, but external diameter alone does not determine cutting resistance. Rice stems possess a heterogeneous internal structure and their mechanical response depends on structural organization across several scales. Zhou *et al*. (2019) examined the relationship between multiscale structural characteristics and the elastic modulus of rice stems, demonstrating the importance of internal organization in interpreting macroscopic behaviour. Direct cutting measurements are therefore needed to establish how dimensional differences translate into force and energy requirements. Shivashimpar *et al*. (2023) addressed this requirement through an instrumented system for measuring cereal cutting energy, incorporating crop characteristics and operational variables such as cutting velocity and blade geometry. For crop characterization, the implication is that stem measurements should be taken at a clearly specified internode and used to define subsequent cutting experiments rather than to estimate machine power without mechanical validation.

The relevance of stem properties extends beyond the initial cutting operation. During threshing, rice stalks experience combinations of impact, compression, bending and tension that can generate fragments and increase the material requiring separation from grain. Tang *et al*. (2019) investigated structural damage in rice stalks undergoing threshing, while Tang *et al*. (2021) examined their breaking paths under combined loading. Liu *et al*. (2022) subsequently demonstrated that threshing-gap configuration influences straw damage and the proportion of material other than grain in the threshing output. These studies indicate that crop–machine compatibility should consider the behaviour of both grain and vegetative material. Measurements of stem and hill geometry can help establish representative crop inputs for such investigations, although the resulting damage and separation performance must be measured directly.

Moisture condition provides a complementary description of the crop at harvest. Grain moisture is relevant to grain damage and processing quality, whereas straw moisture characterizes the vegetative material passing through the cutting and handling systems. In Champa rice, Kyani *et al*. (2025) found that harvesting method, grain moisture content and their interaction affected harvest losses and grain-quality outcomes. Their findings demonstrate that harvesting performance cannot be interpreted independently of the moisture conditions under which it was measured. Accordingly, grain and straw moisture should be reported separately and on an explicitly stated basis. Recording these properties alongside crop dimensions allows subsequent engineering comparisons to distinguish differences in geometry from differences in material condition.

At the stand scale, hill density, row spacing and productive stems per hill describe different aspects of crop organization. Hill density expresses the number of plant groups per unit area, while productive stems per hill describes the number of grain-bearing stems within each group. These quantities are therefore complementary and should not be treated as interchangeable measures of crop density. Clerget *et al*. (2016) investigated the responses of tillering and plant growth to planting density, demonstrating the need to interpret individual-plant development within its population context. Hu et al. (2020) likewise showed that row arrangement and planting density influence yield formation in mechanically transplanted rice. Li *et al*. (2023) distinguished single-stem resistance from whole-hill behaviour: changing hill configuration improved whole-hill lodging resistance without a corresponding significant difference in the single-stem lodging index. This distinction provides a strong rationale for including hill diameter and productive stems per hill alongside stem-level measurements.

Recent research has also connected stand architecture directly with mechanical harvesting outcomes. In five-year field trials, Li *et al*. (2026) examined the effects of row-spacing configuration and cultivar on panicle distribution and mechanical harvest losses. Their results linked improved panicle-position uniformity under wide–narrow row planting with reduced harvesting losses. This evidence strengthens the case for describing both the horizontal arrangement of hills and the vertical distribution of grain-bearing structures. However, panicle length and panicle elevation represent different measurements: the former describes the inflorescence itself, whereas the latter describes its position relative to the ground. Clear definitions are essential when comparing studies or relating crop measurements to header interception and gathering geometry.

Crop properties measured at harvest also reflect management and growing conditions. Zhang *et al*. (2016a) demonstrated that nitrogen application affected

anatomical characteristics associated with lodging resistance in japonica rice. In a related investigation, Zhang *et al*. (2016b) showed that reduced structural carbohydrate content and lignin deposition contributed to weaker culms under higher nitrogen application. Chen *et al*. (2021) further reported changes in yield and lodging resistance under different fertilization configurations in mechanically direct-seeded rice. Consequently, dimensions reported for a variety should be interpreted in relation to its cultivation conditions, maturity stage and sampling procedure. A cultivar name alone is insufficient to establish that measurements from different locations or management systems represent equivalent harvesting conditions.

Ranjit Sub-1 provides a relevant case for characterization because it was developed for submergence-prone rice production environments in northeastern India. The identification of *Sub1A* and the development of marker-assisted backcrossing approaches established the genetic and breeding foundations for introducing submergence tolerance into widely cultivated rice backgrounds (Xu *et al*., 2006; Neeraja *et al*., 2007). Specifically, Chetia et al. (2018) described the introgression of the *Sub1* region into Ranjit and the recovery of important characteristics of the recurrent parent. This breeding history establishes the identity and production relevance of Ranjit Sub-1, but does not establish its harvesting properties. Those properties require measurements from the crop stand at the stage and under the conditions relevant to harvesting.

Despite advances in understanding rice architecture and crop–machine interactions, the harvest-relevant characteristics of Ranjit Sub-1 remain insufficiently documented to inform cultivar-specific machinery evaluation. Addressing this gap requires an integrated assessment of crop geometry, moisture condition and stand structure at harvest. Accordingly, this study characterized nine properties of Ranjit Sub-1 paddy: plant height, panicle dimension, stem diameter at the first internode, productive stems per hill, hill diameter, grain moisture content, straw moisture content, hill density and row spacing. The objectives were to quantify their distributions and relative variability and to interpret their relevance to crop cutting, gathering and feeding. This characterization establishes a baseline for the sampled production conditions and provides a basis for selecting representative crop conditions for subsequent mechanical testing and harvesting-system evaluation.

Materials and Methods

Experimental site and crop material

The study was conducted in a farmer's field in Chhaygaon, Assam, India, to characterize the plant architecture and harvest-relevant engineering properties of Ranjit Sub-1 paddy. The crop was established by direct seeding and measurements were taken at the harvesting stage.

Nine properties were evaluated: plant height, panicle dimension, stem diameter at the first internode, productive stems per hill, hill diameter, grain moisture content, straw moisture content, hill density and row spacing. These properties were selected to characterize crop geometry, moisture condition and spatial stand structure relevant to cutting, gathering and feeding operations. The experimental workflow was shown in Fig. 1.

Sampling and experimental records

The experimental dataset comprised 25 records collected at the harvesting stage. Each record represented an individual paddy sampling unit established using the quadrat sampling method. The sampling units were

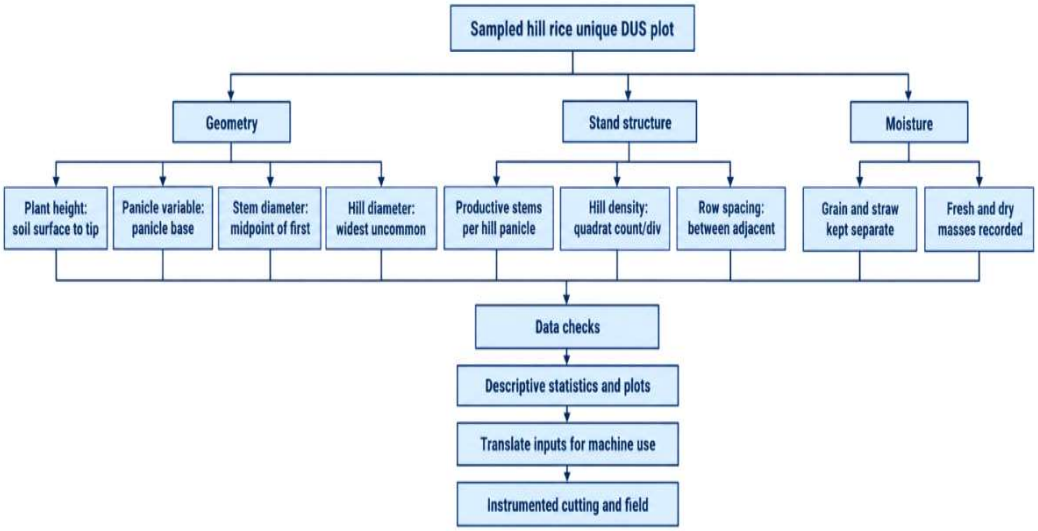


Fig. 1 : Workflow for characterizing the harvest-relevant properties of Ranjit Sub-1.

distributed across the experimental field to capture spatial variability in crop growth and yield attributes. Measurements were recorded separately for each sampling unit, and a unique identifier was assigned to link field observations with the analytical dataset.

Plant- and hill-level observations were linked to their corresponding sampling units. Stem diameter was measured using an INSIZE digital caliper (Model 1108-150; measurement range: 0–150 mm; resolution: 0.01 mm; accuracy: ±0.02 mm). Multiple stems measured within the same hill were treated as subsamples, while repeated measurements of the same stem were treated as technical measurements. Neither was considered an independent field replication. Repeated measurements were averaged to obtain a representative stem-diameter value for each sampling unit, and the aggregated values were retained for subsequent statistical analysis.

Hill density was determined using a 0.5 m × 0.5 m quadrat (0.25 m^2) at each of the 25 sampling locations. The quadrat was positioned according to the predefined field-sampling procedure, and the number of hills within each quadrat was recorded. Hill density was expressed as the number of hills per square meter. Grain and straw samples were collected from the corresponding sampling units to determine moisture content. Where multiple subsamples were pooled, the pooled material was treated as one analytical unit, and the constituent subsamples were not counted as independent observations. All measurements were linked to their respective sampling-unit identifiers for subsequent statistical analysis.

The observations were compiled in an electronic spreadsheet and checked for transcription errors, missing entries and unit consistency before descriptive analysis and graphical presentation. Published values used for contextual comparison were maintained separately and excluded from calculations of experimental summary statistics.

Measurement of crop geometry and productive stems

Plant height : Plant height was measured at the harvesting stage using a measuring scale with a resolution of 1 mm. The measurement was taken from the soil surface to the tip of the tallest panicle, excluding any unusually bent or broken portions. Plants were measured in their natural standing position without stretching or straightening the stems. Five representative plants were selected from each sampling hill, and their individual heights were recorded in millimeters. The mean height of the five plants was calculated to obtain the representative plant-height value for each hill.

Panicle dimension : Panicle length was measured at the harvesting stage using an INSIZE digital caliper (Model 1108-150; resolution: 0.01 mm), where applicable to the instrument's measurement range. The measurement was taken from the base of the panicle, at the point of attachment to the panicle-bearing stem, to the tip of the terminal spikelet. Each panicle was positioned straight without applying tension or deforming its natural structure. Five representative panicles were selected from each sampling unit and their lengths were recorded in milli meters. The arithmetic mean of the five measurements was calculated to obtain the representative panicle length for each sampling unit.

Stem diameter : Stem diameter was measured at the first above-ground internode using an INSIZE digital caliper (Model 1108-150; resolution: 0.01 mm). Measurements were taken at the midpoint of the internode, avoiding the node and any visibly damaged tissue. Five representative stems were selected from each sampling hill. For each stem, two diameter measurements were taken at perpendicular orientations to account for potential variation in stem cross-section. The arithmetic mean of the two measurements was calculated to obtain the stem diameter for each stem. The mean of the five stem-diameter values was then used as the representative value for each sampling hill. All measurements were expressed in milli meters.

Productive stems per hill : The number of productive stems per hill was determined by counting all panicle-bearing stems within each sampled paddy hill at the harvesting stage. Stems bearing at least one panicle were classified as productive, whereas non-panicle-bearing tillers were excluded. Counts were recorded separately for each sampling hill and expressed as the number of productive stems per hill. Each hill was treated as a sampling unit and the recorded counts were linked to the corresponding sampling-unit identifiers for subsequent statistical analysis.

Hill diameter : Hill diameter was measured across the basal stem bundle of each sampled paddy hill using an INSIZE digital caliper. Measurements were taken at a consistent position near the base of the stem bundle, avoiding loose or projecting tillers. The diameter was recorded in millimeters for each sampling hill and linked to its corresponding sampling-unit identifier for subsequent statistical analysis.

Determination of grain and straw moisture content

Grain and straw moisture contents were determined separately at the harvesting stage using the oven-drying method. Representative grain and straw samples were

collected from the corresponding sampling units and weighed to obtain their initial wet masses. The samples were dried in a hot-air oven at 105 ± 2°C until a constant mass was achieved. The dried samples were then weighed to determine their dry masses. Moisture content was calculated on a wet basis and expressed as a percentage using the difference between wet and dry masses relative to the initial wet mass. Where multiple subsamples were pooled, each pooled sample was treated as one analytical unit and its constituent subsamples were not considered independent observations. Wet-basis moisture content represents the mass of water as a percentage of the initial sample mass:

$$MC_{wb} = \frac{m_f - m_d}{m_f} \times 100 \quad (1)$$

where, MC_{wb} is moisture content % wet basis, m_f is the initial fresh mass and m_d is the dry mass, with both masses expressed in the same units. Grain and straw moisture values were analysed separately to characterize the moisture condition of the grain and vegetative material at harvest.

Measurement of hill density and row spacing

Hill density was determined by counting the hills within sampling quadrats of known area and calculated as:

$$D_h = \frac{N_h}{A_q} \quad (2)$$

where, D_h is hill density hills m^{-2}, N_h, is the number of hills counted and A_q is the quadrat area m^{-2}.

Row spacing was measured as the perpendicular distance between the centrelines of adjacent rows and expressed in millimetres. Hill density and row spacing were used to characterize the spatial arrangement of the crop stand at harvest.

Statistical analysis

The experimental dataset was screened for missing values, duplicate entries, unit consistency and numerical plausibility before analysis. Count variables were checked for integer values, and moisture contents were checked against the range of 0–100%. Unusual observations were examined against the original records before inclusion in the analysis.

Descriptive statistics were calculated for each property, including the number of valid observations, arithmetic mean, sample standard deviation, standard error, median, minimum, maximum, range and coefficient of variation. Bias-corrected sample skewness and excess kurtosis were used to describe distributional asymmetry and tail characteristics, respectively.

The arithmetic mean and sample standard deviation were calculated as:

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \quad (3)$$

where, x_i is an individual observation and n is the number of valid observations for the corresponding property. Standard error and coefficient of variation were calculated as:

$$s = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}} \quad (4)$$

The coefficient of variation was used to compare relative variability among the measured properties. Where sampling independence and distributional assumptions were appropriate, the 95% confidence interval for the mean was calculated using t-distribution:

$$SE = \frac{s}{\sqrt{n}} \quad (5)$$

where, $t_{0.975,\,n-1}$ is the critical value corresponding to n-1 degrees of freedom. Technical replicate readings, where available, were averaged within each sampling unit before calculating descriptive statistics.

Harvesting-performance data

Harvesting-performance observations were analysed separately from crop-characterization records. The trial structure comprised three grain moisture levels and four forward speeds, with three independent harvesting runs per combination, giving 36 runs. The 25 crop-characterization records were not treated as harvesting-trial replications.

Hourly fuel consumption, fuel energy input rate and the ratio of active harvesting capacity to theoretical field capacity were summarized by moisturespeed combination. Repeated instrument readings within a run were treated as technical measurements rather than additional independent replications. Differences were expressed as absolute changes, percentage changes or percentage-point differences, as appropriate.

Fuel energy input rate was derived from hourly fuel consumption and was not interpreted as independent evidence of treatment effects. Capacity calculations used active harvesting time, excluding the field delays specified in Section 2.7.

Harvesting-performance results were evaluated

descriptively. Differences among moisturespeed combinations were interpreted as numerical trends, without claims of statistical significance.

Experimental design for harvesting-performance evaluation

Harvesting performance was evaluated at three grain moisture levels (19.78%, 21.61% and 23.44%, wet basis) and four forward speeds (0.53, 0.70, 0.95 and 1.15 km h^{-1}), comprising 12 moisturespeed combinations. The response variables were hourly fuel consumption, calculated fuel energy input rate and the ratio of active harvesting capacity to theoretical field capacity.

Trials were conducted on 2223 November 2023 in a field of transplanted Ranjit Sub-1 rice. Harvesting performance was evaluated over measured passes and grain moisture content was determined using a digital grain moisture meter.

Harvesting was performed using a Kubota DC-70 Plus track-type combine harvester equipped with a 51 kW engine and a working width of 2.07 m. The nominal cutting height was 0.15 m, and the threshing drum speed was maintained at 560 rpm. The conveyor chain operated at the factory setting and the cleaning fan was set to medium-high. Between runs, interventions were limited to removing minor straw accumulations from the sieve and adjusting the cutter-bar height where localized lodging required intervention.

Before each recorded run, the engine was warmed up for 15 min and track tension, belts and cutter-bar components were inspected. A 50 m travel run without harvesting was then performed to check operating stability. Forward speed was determined from the time required to traverse a measured 50 m course using distance markers and a digital stopwatch.

Fuel consumption was measured separately for each run using the fuel top-up method and a graduated cylinder with a resolution of 10 mL. Harvested dimensions were measured using a metric tape with a resolution of 0.01 m, while elapsed time was recorded using a digital stopwatch with a resolution of 0.01 s. Recorded time included only active harvesting within the plot boundary; headland turning, corner idling and unexpected mechanical stoppages were excluded. Capacity calculated using this time boundary was therefore defined as active harvesting capacity. Its ratio to theoretical field capacity was expressed as a percentage and distinguished from overall field efficiency based on total elapsed field time.

Measurement of hourly fuel consumption

Fuel consumption was measured separately for each harvesting run using the fuel top-up method. The volume of fuel required to restore the tank to its initial reference level after each run was measured using a graduated cylinder with a resolution of 10 mL and recorded as the fuel consumed. The corresponding active harvesting time was measured using a digital stopwatch with a resolution of 0.01 s. Headland turning, corner idling and unexpected mechanical stoppages were excluded from the recorded harvesting time. Hourly fuel consumption was calculated as:

$$FC = \frac{V_c}{t} \tag{6}$$

where, FC is hourly fuel consumption (L h^{-1}), V_c is the volume of fuel consumed (L), and t is the operating time (h). The calculated values were compared across the different grain moisture levels and forward speeds.

Calculation of fuel energy input rate

Fuel energy input rate was calculated from hourly fuel consumption using the energy content of the fuel. It represents the rate of chemical energy supplied through fuel consumption rather than the mechanical power output of the harvesting machine. The calculation was performed using:

$$E_f = \frac{FC \times \rho_f \times LHW}{3.6} \tag{7}$$

where, E_f is fuel energy input rate (kW), FC is hourly fuel consumption (L h^{-1}), is fuel density (kg L^{-1}) and LHV is the lower heating value of the fuel (MJ kg^{-1}). The conversion factor 3.6 was used to express the result in kilowatts.

Determination of field efficiency

Field efficiency was calculated as the ratio of effective field capacity to theoretical field capacity and expressed as a percentage:

$$\eta_f = \frac{EFC}{TFC} \times 100 \tag{8}$$

where, η_f is field efficiency (%), EFC is effective field capacity (ha h^{-1}) and TFC is theoretical field capacity (ha h^{-1}).

Theoretical field capacity was calculated using:

$$TFC = \frac{W \times S}{10} \tag{9}$$

where, W is the effective working width (m), and S is forward speed (km h^{-1}).

Effective field capacity was determined from the

harvested area and the corresponding harvesting time:

$$EFC = \frac{A_h}{T_h} \quad (10)$$

where, A_h is the harvested area (ha) and T_h is the time required to harvest that area (h). Harvested dimensions were measured using a metric tape with a resolution of 0.01 m. Area measured in square metres was converted to hectares by dividing by 10,000. Active harvesting time was recorded using a digital stopwatch with a resolution of 0.01 s and converted to hours.

The timing boundary excluded headland turning, corner idling and unexpected mechanical stoppages. Consequently, the calculated capacity ratio describes performance during active harvesting and does not represent overall field efficiency based on total elapsed field time. The same calculation procedure was applied to all moisturespeed combinations.

Results and Discussion

Overall variability

The measured characteristics differed in relative variability (Table 1, Fig. 2). Productive stems per hill exhibited the highest reported coefficient of variation (CV; 24.26%), whereas plant height exhibited the lowest (4.89%). Thus, comparatively uniform crop height occurred alongside greater variation in the number of panicle-bearing stems within individual hills. These contrasting patterns show that plant height alone does not adequately describe the crop material available for engagement by a harvesting mechanism.

Hill diameter and hill density exhibited CVs of 13.11% and 13.89%, respectively, indicating additional variation in bundle dimensions and spatial crop arrangement. Straw moisture also varied more than grain moisture. Consequently, representative harvesting experiments should encompass variation in hill structure and moisture as well as plant dimensions. These descriptive differences identify conditions for subsequent testing; they do not establish which characteristic has the greatest effect on harvesting performance.

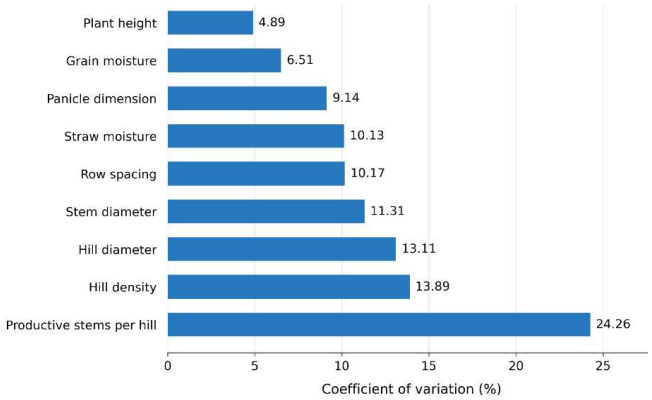


Fig. 2 : Relative variability of properties of Ranjit Sub-1 paddy, expressed as coefficient of variation (%).

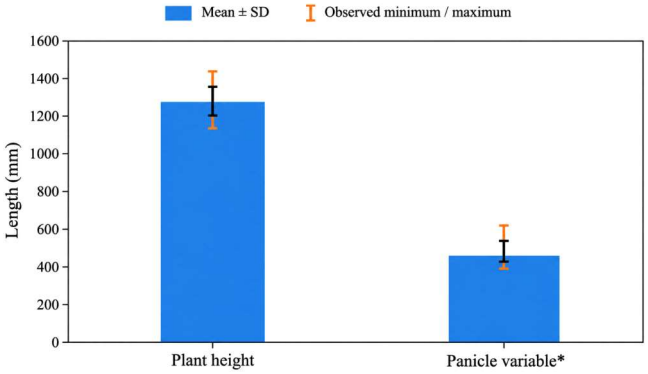


Fig. 3 : Mean plant height and measured panicle dimension of Ranjit Sub-1 paddy.

Plant height and panicle dimension

Plant height averaged 1292.01 ± 63.22 mm, with observations ranging from 1184.50 to 1422.20 mm (Fig. 3). The median of 1277.90 mm and skewness coefficient of 0.40 indicated slight positive asymmetry. The relatively low coefficient of variation (4.89%) suggested comparatively uniform plant stature within the sampled stand. Nevertheless, the observed height range of 237.70 mm represents variation that should be accommodated

Table 1 : Descriptive statistics of plant architecture and harvest-relevant engineering properties of Ranjit Sub-1 paddy.

Variable	Unit	Mean	SD	CV %	Min	Max
Plant height	mm	1292.01	63.22	4.89	1184.50	1422.20
Panicle variable	mm	463.80	42.41	9.14	409.20	588.00
Stem diameter	mm	6.39	0.72	11.31	4.81	7.65
Productive stems per hill	stems/hill	10.12	2.45	24.26	6.00	14.00
Hill diameter	mm	66.60	8.73	13.11	49.50	84.30
Grain moisture	% w.b.	21.98	1.43	6.51	18.87	24.35
Straw moisture	% w.b.	40.34	4.09	10.13	31.56	46.36
Hill density	hills/m²	24.72	3.43	13.89	20.00	30.00
Row spacing	mm	217.20	22.08	10.17	200.00	250.00

when evaluating crop interception and conveying mechanisms. These measurements provide a geometric reference for testing vertical adjustment ranges; determination of suitable operating settings additionally requires information on panicle position, lodging and field-surface conditions.

The measured panicle dimension averaged 463.80 ± 42.41 mm and ranged from 409.20 to 588.00 mm. Its coefficient of variation was approximately 9.14%, indicating greater relative dispersion than plant height. Positive skewness (1.02) and excess kurtosis (1.55) indicated a distribution with an extended upper tail and greater tail weight than a normal distribution. Consequently, the mean alone did not fully describe the variation in this trait, supporting the inclusion of dispersion and range statistics in crop characterization. The engineering interpretation of this measurement depends on its anatomical endpoints, particularly whether it describes panicle length or panicle elevation above the soil surface.

Stem and hill dimensions

Stem diameter at the first above-ground internode averaged 6.39 ± 0.72 mm and ranged from 4.81 to 7.65 mm (Fig. 4). The coefficient of variation was 11.31%, indicating variation in stem size within the sampled stand. The observed diameter range provides a basis for selecting representative stems for cutting tests. However, the relationship between diameter and cutting resistance also depends on stem wall thickness, cross-sectional geometry, tissue condition and blade configuration. Instrumented cutting experiments incorporating crop dimensions and blade operating parameters are therefore required to determine cutting force and energy requirements, consistent with the approach reported by Shivashimpar *et al*. (2023).

Hill diameter averaged 66.60 ± 8.73 mm, with a minimum of 49.50 mm and a maximum of 84.30 mm. The corresponding coefficient of variation was approximately 13.11%, showing greater relative variability in hill diameter than in individual stem diameter. This difference indicates that stem-level measurements do not fully describe variation in the dimensions of the bundles encountered during gathering and conveying. The observed hill-diameter range defines the bundle sizes represented in the sample and can guide the selection of test material for evaluating passage through gathering and feeding mechanisms. Operational clearances must additionally account for bundle deformation, orientation and misalignment during machine engagement. Hill diameter alone does not determine bundle packing density

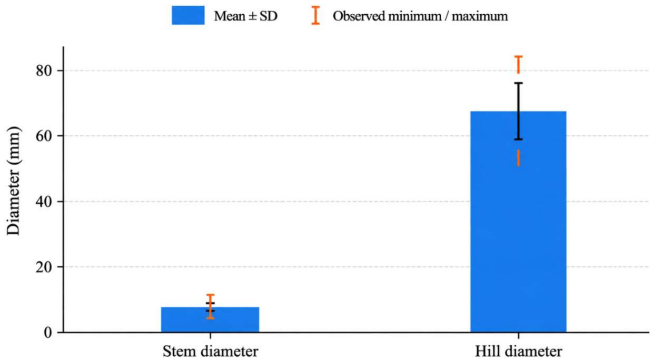


Fig. 4 : Stem and hill diameters of Ranjit Sub-1 paddy.

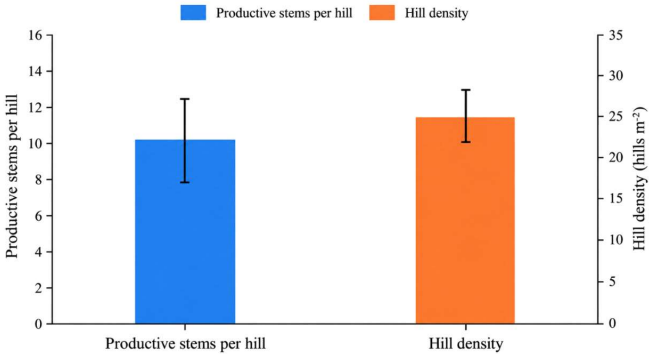


Fig. 5 : Productive stems per hill and hill density of Ranjit Sub-1 paddy.

or the gripping pressure required for reliable conveyance.

Productive stems and spatial stand structure

Productive stems per hill averaged 10.12 ± 2.45 stems hill^{-1} and ranged from 6 to 14, while hill density averaged 24.72 ± 3.43 hills m^{-2} and ranged from 20 to 30 hills m^{-2} (Fig. 5). Productive-stem number exhibited greater relative variability than hill density, indicating that variation in stem aggregation within hills accompanied variation in the spatial concentration of hills. These properties describe different components of stand structure and should be considered jointly when selecting crop arrangements for cutting and feeding experiments. Productive stems per hill characterizes the number of grain-bearing stems within each bundle, whereas hill density describes the frequency of bundles encountered per unit ground area. Productive-stem density per square metre was not calculated because correspondence between the hill-level observations and density-sampling areas was not established.

Row spacing averaged 217.20 ± 22.08 mm and comprised three recorded levels: 200 mm in 14 observations, 220 mm in four observations and 250 mm in seven observations. These levels accounted for 56%, 16% and 28% of the records, respectively (Fig. 6). The pooled mean therefore summarizes the sampled spacing configurations but does not represent a spacing observed in the field. Reporting the individual levels and their

frequencies preserves this distinction and provides a clearer basis for evaluating gathering mechanisms under the recorded crop arrangements.

Grain and straw moisture content

Grain moisture content averaged 21.98 ± 1.43% on a wet basis and ranged from 18.87 to 24.35% (Fig. 6). Twenty-two observations (88%) fell within the 20–25% interval highlighted in the figure, while three observations were below 20%. These results describe the grain moisture conditions at sampling and provide a reference for subsequent harvesting trials. Moisture must nevertheless be interpreted alongside harvesting method: Kyani *et al*. (2025) reported that grain moisture, harvesting method and their interaction affected rice losses and grain-quality outcomes. Accordingly, the observed moisture distribution does not establish an optimum harvesting moisture content for Ranjit Sub-1 without corresponding measurements of grain loss, damage and milling recovery.

Straw moisture content averaged 40.34 ± 4.09% on a wet basis and ranged from 31.56 to 46.36%. Its coefficient of variation was approximately 10.1%, compared with 6.5% for grain moisture, indicating greater relative variability in the vegetative material. The difference between mean straw and grain moisture was 18.36 percentage points, demonstrating that grain moisture alone did not characterize the moisture condition of the entire crop. Separate measurement of both components is therefore necessary when defining crop conditions for cutting, feeding and threshing experiments. The present results establish the moisture ranges represented in the sampled stand; their effects on cutting resistance, conveying behavior and grain damage require direct mechanical evaluation.

Effect of grain moisture content and forward speed on hourly fuel consumption

Mean hourly fuel consumption (Fig. 7) increased from 13.80 L h^{-1} at 19.78% grain moisture content to 14.77 L h^{-1} at 21.61% and 15.46 L h^{-1} at 23.44% moisture content, wet basis. The difference between the lowest and highest moisture levels was 1.66 L h^{-1}, equivalent to approximately 12.03%.

Hourly fuel consumption also increased with forward speed at each moisture level. As speed increased from 0.53 to 1.15 km h^{-1}, consumption increased from 12.53 to 15.11 L h^{-1} at 19.78% moisture, from 13.41 to 16.17 L h^{-1} at 21.61% moisture, and from 14.03 to 16.92 L h^{-1} at 23.44% moisture. The lowest reported hourly consumption occurred at 19.78% moisture and 0.53 km

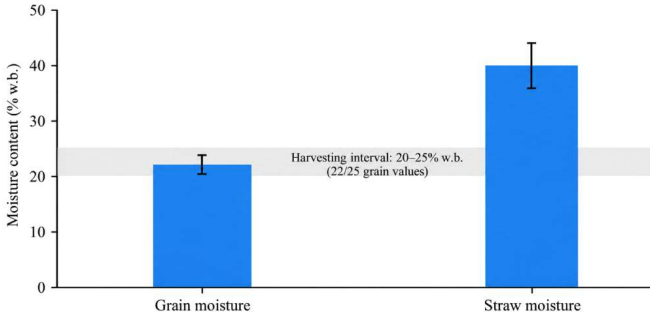


Fig. 6 : Grain and straw moisture contents of Ranjit Sub-1 paddy at harvest, expressed on a wet basis.

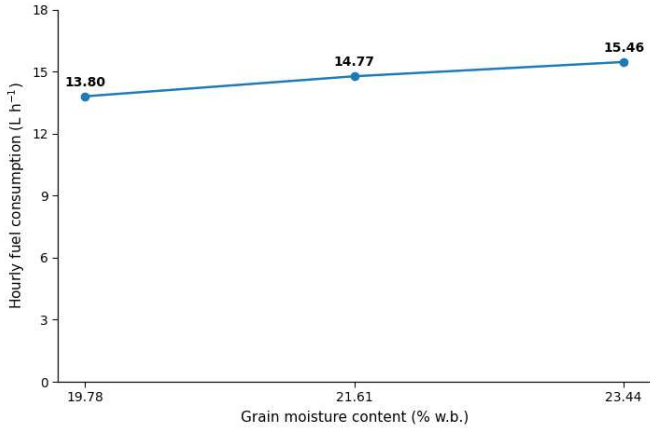


Fig. 7 : Effect of grain moisture content on hourly fuel consumption.

h^{-1}, whereas the highest occurred at 23.44% moisture and 1.15 km h^{-1}. These comparisons describe numerical trends; statistical significance and a moisture–speed interaction were not established.

The observed patterns may reflect increased crop throughput at higher forward speeds and changes in crop-handling resistance with moisture content. However, throughput and component loads were not separately quantified, so these explanations remain provisional.

Lower hourly fuel consumption does not necessarily indicate lower fuel use per hectare or tonne, because harvesting capacity and grain throughput may also vary with operating conditions. As matching run-level records were not verified for these calculations, area-specific and grain-specific fuel consumption are not reported. The findings therefore identify differences in hourly fuel demand without establishing an optimum operating condition, improved fuel-use efficiency or environmental savings.

Fuel energy input rate

The calculated fuel energy input rate (Fig. 8) increased from a mean of 136.39 kW at 19.78% grain moisture content to 145.95 kW at 21.61% and 152.74 kW at 23.44% moisture content. This represented an

increase of 16.35 kW (11.99%) between the lowest and highest moisture levels.

At a forward speed of 0.53 km h^{-1}, the calculated input rate increased from 123.80 to 138.62 kW between the lowest and highest moisture levels. At 1.15 km h^{-1}, the corresponding values increased from 149.29 to 167.17 kW. These results indicate an increase in fuel energy input rate with increasing grain moisture content and forward speed.

The higher input rate at increased forward speeds related to the greater crop throughput and corresponding fuel demand. Similarly, wetter crop material may increase the resistance during threshing and crop handling, contributing to higher fuel consumption. Since the fuel energy input rate was calculated from fuel consumption, it represents the energy equivalent of the fuel used per unit time rather than an independent measurement of mechanical power output.

Effect of grain moisture content and forward speed on field efficiency

Mean field efficiency (Fig. 9) decreased from 68.02% at 19.78% grain moisture content to 59.76% at 21.61% and 50.30% at 23.44% moisture content. The decline between the lowest and highest moisture levels was 17.72 percentage points, equivalent to a relative reduction of 26.05%.

At 19.78% moisture content, field efficiency decreased from 78.38% to 60.76% as forward speed increased from 0.53 to 1.15 km h^{-1}. At 21.61% moisture content, the corresponding values decreased from 67.57% to 54.43%. At 23.44% moisture content, field efficiency ranged from 46.97% to 54.05% across the tested forward speeds.

The lower field efficiency at higher moisture contents associated with increased crop-handling resistance and operational time. The results indicate that both grain moisture content and forward speed influenced field efficiency under the tested conditions.

Engineering implications and study limitations

The characterization of Ranjit Sub-1 provides crop dimensions and moisture conditions for selecting representative material for machinery evaluation. The observed plant-height range of 1184.50–1422.20 mm can guide the adjustment ranges examined for crop interception and conveying mechanisms. Stem diameters of 4.81–7.65 mm and hill diameters of 49.50–84.30 mm define specimen-size ranges for cutting and bundle-handling tests. Productive stems per hill, hill density and row spacing describe complementary aspects of crop

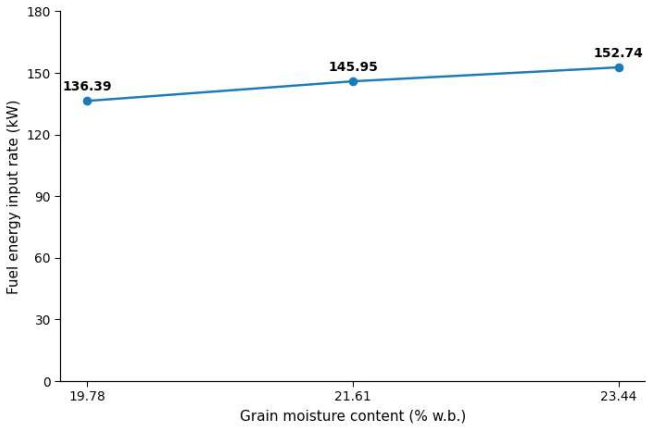


Fig. 8 : Effect of grain moisture content on fuel energy input rate.

arrangement, while grain and straw moisture contents characterize the material conditions under which mechanical responses should be evaluated.

The harvesting trials provided observations of hourly fuel consumption and active harvesting capacity relative to theoretical field capacity. Fuel energy input rate was calculated from fuel consumption and therefore represents a derived quantity rather than an independent measurement of mechanical power. These results describe operating patterns across the evaluated moisture–speed combinations. However, the dimensional measurements and hourly fuel-consumption values do not independently establish suitable motor power, blade configuration or an optimum operating speed. Instrumented cutting and feeding tests remain necessary to relate crop characteristics to mechanical requirements, consistent with the approach described by Shivashimpar *et al*. (2023).

Fig. 10 presents selected Ranjit Sub-1 measurements alongside published PR-126 values reported by Dwivedi and Chauhan (2025). This comparison provides context across studies rather than a controlled test of cultivar differences. Differences in measurement definitions,

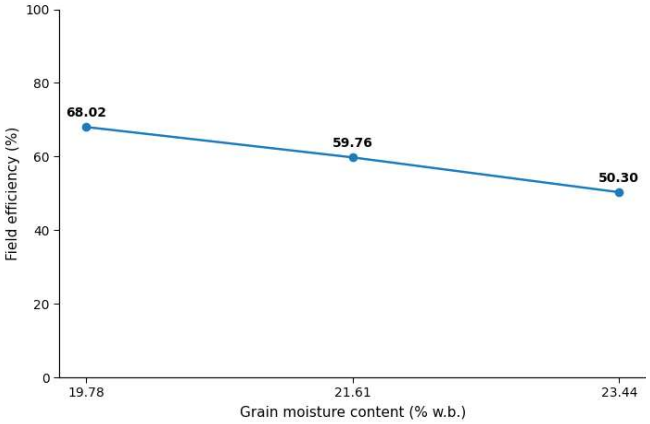


Fig. 9 : Effect of grain moisture content on field efficiency.

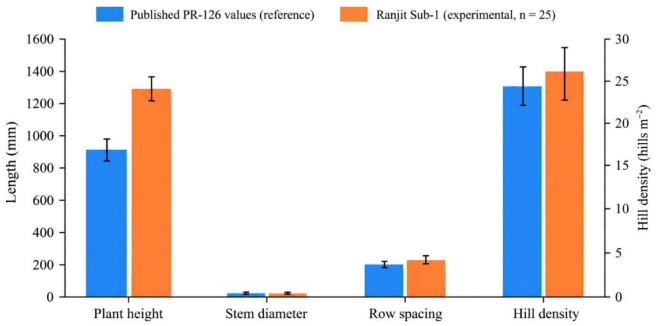


Fig. 10 : Selected crop and stand characteristics of Ranjit Sub-1 paddy alongside published PR-126 reference values from Dwivedi and Chauhan (2025).

maturity, cultivation conditions and field observation procedures must be considered before attributing numerical contrasts to cultivar identity. Comparisons of panicle traits additionally require consistent anatomical measurement endpoints.

The findings apply to the evaluated crop stand and operating conditions and do not establish performance across seasons, fields or management systems. Recorded harvesting time excluded headland turning, corner idling and unexpected mechanical stoppages; consequently, the reported capacity ratio does not represent overall field efficiency based on total elapsed field time. Harvesting comparisons were descriptive, and statistical significance and a moisture–speed interaction were not established. Direct cutting force, stem mechanical properties, engine shaft power, grain losses, grain damage and environmental impacts were not measured. Verified fuel consumption per hectare or tonne was also not established; therefore, improved fuel-use efficiency and environmental savings cannot be concluded from hourly consumption alone. Further evaluation should combine instrumented mechanical tests with replicated harvesting trials that record total field time, matched fuel use, harvested area, grain output and harvesting losses.

Conclusion

The study established crop-specific reference conditions for evaluating mechanized harvesting of Ranjit Sub-1 rice. Productive stems per hill exhibited substantially greater variability than plant height (CV: 24.26% versus 4.89%), supporting the inclusion of hill structure and stem aggregation alongside crop dimensions in machinery testing. Grain and straw moisture contents averaged 21.98 ± 1.43% and 40.34 ± 4.09% wet basis, respectively, demonstrating the need to characterize both grain and vegetative material. Across grain moisture levels of 19.78–23.44%, mean hourly fuel consumption increased from 13.80 to 15.46 L h^{-1}, while the active harvesting capacity ratio decreased from 68.02% to 50.30%. These descriptive trends identify moisture and forward speed as priorities for further operational evaluation; they do not establish statistically significant treatment effects or an optimum operating condition. The environmental relevance of this work lies in providing a crop-specific basis for testing harvesting adjustments against measurable resource-use targets: fuel consumption per hectare or tonne, grain losses and grain damage. Reductions in these indicators could lower fuel-related emissions and conserve the agricultural inputs embodied in recovered grain. Demonstrating those benefits requires matched measurements of fuel use, harvested area, grain output and total field time. The present contribution therefore supports the evaluation of eco-friendly harvesting strategies without claiming environmental savings that were not measured.

Disclaimer (Artificial Intelligence)

Generative artificial intelligence (ChatGPT, OpenAI) was used to assist in editing and refining the language of this manuscript. The authors reviewed the revised text and accept full responsibility for the accuracy, integrity, and final content of the manuscript.

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Competing interests

The authors declare that no competing interests exist.

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