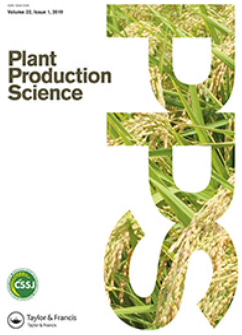


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# Fissured grain and head rice yield of crops harvested manually or by combine at different ripening stages in Cambodia

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**ABSTRACT**
Combine has been well adopted by smallholders in lowlands of Cambodia and is contributing to the development of mechanized rice production for commercial purposes. Broken rice is a major issue for the commercial rice product, and fissured grain at harvest leads to broken rice and lowers head rice yield (HRY) during milling. Factors that determine grain fissures and broken rice were obtained from three studies: an on-farm study of fissured grain, a research station experiment of fissured grain and broken rice harvested at different ripening stages and a mill study of fissured and broken rice during drying and milling processes in Cambodia. There was significant variation in fissured rice percentage among 20 farms sampled, and the fissured grain was negatively correlated with grain moisture content at harvest. Time of harvesting was crucial, as delay in harvesting after 25 days after flowering (DAF) often resulted in lower grain moisture content and higher fissured grain, which subsequently reduced HRY. However, the optimum time of harvesting varied across four seasons for crops harvested manually or by combine. In some years, crops harvested at 35 DAF had rather low per cent fissured grain with subsequently high HRY, this may have been associated with slightly lower temperatures. The mill study showed that fissured grain developed during the drying, storage and milling processes. It is concluded that while grain moisture content at the time of harvest may be used as an indication of subsequent HRY, the latter was more strongly related to fissured grain at harvest.

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Rice; grain fissures; harvesting time; head rice yield; combine

## 1. Introduction

Rice accounts for over 80% of Cambodia's cropping area and 50% of the agriculture sector output, and it is mostly consumed domestically but the export market has increased sharply in the last 5 years. Seventy-five per cent of Cambodian rice is produced in the main wet season under rainfed systems. The cost of labour required for rice production has risen as a result of alternative employment opportunities. As a result, combine harvester use has increased in rice production, replacing manual labour for harvesting. In Cambodia, from 2006 to 2014, there was rapid emergence of reapers and combine harvesters, and the statistical records show that in 2006, there were 325 units (~300 reapers), but this increased up to 5506 combine harvesters in 2014 (Department of Agricultural Engineering, 2016).

With the increased marketing of rice, it is important to produce rice of high quality, particularly high head rice yield (HRY) (i.e. the portion of milled rice that are whole kernels or at least 75% original kernel length as a mass percentage of rough rice) with low broken rice percentage. HRY is affected by factors prior to, at and after harvesting. Siebenmorgen et al. (2013) reviewed factors determining HRY in the field. Appropriate post-harvest drying of rough rice is important for minimizing the development of grain fissures and subsequent broken rice at milling and thus, maximizing HRY. Grain fissures with adsorption of moisture particularly with grain of low moisture content at drying. The use of artificial dryers generally produces higher HRY although sun-drying technique can be improved to increase HRY by frequent mixing of grain and drying only in the morning (Meas et al., 2011; Xangsayasane et al., 2019b).

Harvesting is an important operation in rice production. The time at which rice is harvested directly influences the economic return to a producer (the value of harvested rice less certain specified costs such as harvest, storage and drying costs). The primary factors that determine this economic return are rice yield; milling quality, including per cent milled rice and per cent head rice; and drying costs. Rice grain yield from the field, percentage of milled rice and percentage of head rice will decrease and drying costs will

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increase as moisture content at rice harvest increases above the optimal range. HRY increases as grains are filled and immature grain proportion decreases and then peaks before declining with delay in harvesting (Thompson & Mutters, 2006). In our recent study in Cambodia (Bunna et al., 2018), HRY was higher when the crop was harvested at 25 days after flowering (DAF) than crops harvested at 35 and 45 days after harvesting. With the delay in harvest time, grain moisture content generally decreased and fissured grain increased. However, it was concluded that grain moisture content was not a good indicator of optimum harvest time as there was wide variation in HRY for a given grain moisture content. Recently, Xangsayasane et al. () found using glutinous rice in Laos that HRY decreased as harvesting was delayed from 25 to 30 and further to 35 days. However, they did not measure grain moisture content or fissured grain at harvest. Thus, there is need to pinpoint optimum harvesting time to maximize HRY and determine associated grain moisture content and fissured grain for crops harvested between 25 and 35 days.

With the introduction of combine, grain loss at harvesting has become an issue in Cambodia. However, there are little reliable data available on these losses in Cambodia. Bunna et al. (2018) found in research station experiments that the loss increased sharply with delay in harvesting and also that the loss was 2–5% higher in combine harvested crops. It is important to determine grain loss on-farm, as well as determining fissured grain and grain moisture content in commercial crops. Knowledge and identification of points of post-harvest loss are crucial to assist farmers in crop management, particularly for market.

The work reported here included a mill study in which development of fissured grain and broken rice was traced during the drying, dehusking and whitening process at three mills. Thus, the present work aimed to identify factors determining development of fissured grain and broken rice and hence HRY from 3 studies covering commercial fields to mills; 4 seasons on-farm study of fissured grain and grain moisture content at 20 farms, a 2-year study of time of harvest during ripening for crops harvested manually or by combine which was analysed together with our earlier study reported by Bunna et al. (2018), and the mill study.

## 2. Materials and methods

### 2.1. Experiment 1: grain yield, grain fissures and harvesting loss of rice harvested manually or by combine in 20 farms

The experiment was conducted in 20 farms in Takeo Province across 2 years in 4 crop seasons. In the first year, eight wet season crops in Tram Kork and Prey Kabas Districts were harvested in December 2014 and two dry season crops in Kiry Vong District in April 2015 while in the second year eight wet season crops in Tram Kork, Prey Kabas and Bati Districts were harvested in November 2015 and two dry season crops in Sam Rong District in March 2016. In dry season, photoperiod insensitive variety IR504 was grown in these farms while in wet season, photoperiod sensitive aromatic varieties were common. The average size of paddy fields ranged from 0.3 to 0.6 ha. The on-farm experiment adopted the randomized block design with the farmer's field as the block and harvesting method, either manual or combine as the treatment. Statistical analysis was conducted using Crop-start 7.2.

#### 2.1.1. Manual harvesting

In the manual harvesting treatment, three samples were randomly selected using the quadrat. Each sample area was 0.25 $m^2$, and the rice was cut by sickle and moisture content determined, then laid on the stubble for field drying for 1–2 days then bundled and carried for threshing by hand in the field. After threshing grain was cleaned, the grain weight and grain moisture content determined and grain yield expressed at 14% moisture content. To determine fissured grain, 10 rice grains were randomly sampled from each replication, i.e. 30 grains from each treatment were collected and rice husk removed, and then using the table light grain fissures at harvest was determined using NAPHIRE (1997) technical guideline, in the same method described by Bunna et al. (2018). To measure the harvest grain loss in the fields, grain on the soil surface was collected in the area after crop harvesting, then the weight and moisture content were determined.

#### 2.1.2. Combine harvesting

Rice fields used for manual harvesting were also selected to quantify grain lost when harvested by combine (Kubota DC-70, Model G-KH, Osaka, Japan) and to determine fissured grain. The combine operators were asked to operate with appropriate speed depending on the rice crop status. The combine harvested along the paddy field with front blade 3 m wide for 3–6 m, and then the entire paddy rice was collected and the weight and grain moisture content determined. Grain loss by combine and fissured grain were determined in a similar method to the manual harvest, but the sampled area was greater at 2 m × 1 m or 2 m × 0.5 m.

### 2.2. Experiments 2 and 3: grain yield, grain harvesting loss and milling quality of crops harvested manually or by combine at different times during ripening

Two experiments (Experiments 2 and 3) were conducted in the field in two wet seasons at the Cambodian Agriculture Research and Development Institute, Phnom Penh, Cambodia. The soil type was Prateah Lang, and fertilizer management recommended for the soil type was applied, i.e. the rates of 37.8N–23$P_2O_5$–15$K_2O$ kg/ha as basal and at the rate of 12N kg/ha twice during the growth. The medium maturity, aromatic long-grain Phka Rumduol variety (grain length 7.5 mm, grain width 2.1 mm, L/R ratio 3.6) was used in both experiments. The crops were transplanted using a five-row transplanter (Iseki 500DX, Ehime, Japan) on 19 August 2016 and 9 July 2017 and harvested on 18, 23 and 28 November in 2016, and on 6, 11 and 16 November in 2017 (Table 1). These harvest dates corresponded to 25, 30 and 35 DAF. These two experiments were continuation of earlier experiments conducted in 2014 and 2015 reported by Bunna et al. (2018) and followed the same methods. In Table 1 we include the planting and harvesting dates for the 2014 and 2015 experiments, as the four experiments were used to determine yearly variation in milling quality in the present work.

The two experiments adopted a spit-plot design with harvesting method (manual harvesting and combine harvesting) as the main plots and the harvesting time (25, 30 and 35 days after 50% flowering) as sub-plots with three replications. The plot size was 20 m × 3 m for combine harvesting, and 3 m × 2 m for manual harvesting. Harvesting methods and measurements on grain yield, grain loss and fissured grain were determined in the same manner as shown for Experiment 1 mentioned above and also shown in more detail in Bunna et al. (2018) for the 2014–2015 experiments, and hence not repeated here.

After sun-drying of the rice grain collected from each harvest time for both manual and combine harvesting, the sample of 250 g rough rice was milled to determine the milling recovery. The rice sample was milled by dehusker, and the brown rice with less than 3% rough rice was then whitened by polishing for 35 s. The white rice was screened to separate the head rice (whole kernels or at least 75% original kernel length) and broken rice, and HRY determined relative to the original 250 g rough rice.

Mean ambient temperature determined on each harvest day, the mean and mean minimum for 15 days prior to harvest are shown for all experiments in Table 2, while the accumulated temperature calculated as the sum of daily mean temperature between 50% flowering and harvest are shown in relation to HRY in Figure 2(a). In the 2014–2015 experiments of Bunna et al. (2018), harvesting time was 25, 35 and 45DAF, while for 2016–2017 experiments, harvesting time was 25, 30 and 35 days. Mean day-time temperature on the harvest day varied from 30.7 to 35.5°C, while accumulated mean daily temperature between 50% flowering and harvest was 664–686°C for harvest at 25 DAF, between 800 and 804°C at 30 DAF, between 939 and 973°C for 35 DAF and between 1256 and 1265°C for harvests at 45DAF. Fifteen days prior to harvesting, temperature varied from 27.0 to 29.0°C and the temperature at 30–35 DAF harvests was more than 1°C

**Table 2.** Mean temperature (°C) at harvest, and mean and minimum temperature for 15 days before each harvest in 2016 and 2017 (Experiments 2 and 3).

| | | Temperature (°C) | | |
|---|---|---|---|---|
| Year | Harvest time (DAF) | Harvest | 15 days mean | 15 days minimum |
| 2014 | 25 | 27.5 | 28.3 | 24.1 |
| 2014 | 35 | 30.7 | 28.6 | 24.2 |
| 2014 | 45 | 26.9 | 28.7 | 24.1 |
| 2015 | 25 | 28.6 | 29.0 | 24.7 |
| 2015 | 35 | 29.3 | 28.8 | 24.4 |
| 2015 | 45 | 29.4 | 29.0 | 24.7 |
| 2016 | 25 | 28.6 | 27.8 | 25.2 |
| 2016 | 30 | 28.5 | 28.2 | 25.1 |
| 2016 | 35 | 28.0 | 28.2 | 25.0 |
| 2017 | 25 | 27.5 | 27.3 | 24.5 |
| 2017 | 30 | 27.8 | 27.1 | 24.2 |
| 2017 | 35 | 28.6 | 27.0 | 23.9 |

DAF: Days after flowering.
Corresponding values for 2014 and 2015 experiments (Bunna et al., 2018) are also shown.

**Table 1.** Planting time, flowering date and harvesting date for experiments conducted in 2016 and 2017 (Experiments 2 and 3).

| Activities | 2014 | 2015 | 2016 (Expt 2) | 2017 (Expt 3) |
|---|---|---|---|---|
| Sowing/Transplanting date | 25 July | 25 July | 19 August | 9 July |
| 50% flowering | 27 October | 29 October | 19–24 October | 7–11 October |
| Harvest at 25 days | 21 November | 23 November | 18 November | 6 November |
| Harvest at 30 days | – | – | 23 November | 11 November |
| Harvest at 35 days | 1 December | 3 December | 28 November | 16 November |

Corresponding values for 2014 and 2015 experiments from (Bunna et al., 2018) are also shown.

lower in 2017 compared to other years although the difference was smaller for mean minimum temperature for the 15 days.

### 2.3. Mill study

This study was designed to observe development of fissured grain and broken rice at three commercial rice mills. These mills are named here as A, B and C and all established between 2002 and 2007 and were located in Phnom Penh. They used the same milling machines (3 t dehusker model by Long An Machinery Industry Joint Stock Company [LAMICO] and polisher [Vinappro rubber roller] from Vietnam, which is triple polisher and has 3 t/h capacity) but different dryers Mill A, 15 t capacity LAMICO model from Vietnam which takes 18–24 h (45–60°C) to dry depending on paddy moisture content; Mill B, 24 t capacity Yeung Shi model from China which takes 18–24 h to dry (50–75°C); and Mill C, 30 t capacity Suncue model from Taiwan which takes 20–24 h to dry with 45–65°C.

Paddies of IR504 variety grown in dry season and harvested were delivered immediately to each of the three mills. By Cambodian standards, IR504 is an extra-long grain with a length of 9.46–9.49 mm, width of 2.69–2.82 mm and thickness of 2 mm. Samples were collected from each particular step in the mill for determination of grain moisture content, fissured grain and head/broken rice percentage using the same methods mentioned for Experiments 1–3. The fissure grain and head/broken grain were determined at five different times during the postharvest process.

(1) Fissures of wet rice before drying
(2) Fissures of dried rice after drying
(3) Grain fissures immediately prior to milling after storing for 2–4 weeks
(4) Grain fissures, and head and broken brown rice after dehusking
(5) Grain fissures and head and broken white rice after polishing

In the steps 4 and 5, grain was separated to head (>75% length of whole grain) and broken rice, and fissures were determined for the head rice grain only. Husk and bran weights were not obtained in this study.

## 3. Result

### 3.1. Experiment 1

Grain yield was not affected by harvesting methods (Table 3). However, it varied among the farms, and dry season crops produced close to 5000 kg/ha which was 20–30% higher than the yield obtained in the wet season. Harvesting loss of grain in the field was about 5% in combine harvesting and was almost halved with manual harvesting; this was equivalent to 203 and 112 kg/ha, respectively. The grain loss percentage tended to be greater in the dry season than in the wet season. Grain moisture content was not affected by harvesting method, but the variation among the farms was significant, the moisture content ranging from 20% to 27.7%. Dry season crops tended to have slightly higher moisture content than the wet season crop. The range in fissured grain among farms was from

**Table 3.** Mean rice grain yield, grain loss in the field, grain moisture content and fissured grain in two harvest methods (manual and combine) used by 20 farmers across 4 seasons.

| | | Grain yield (kg/ha) | | | Grain loss (%) | | |
|---|---|---|---|---|---|---|---|
| Season | Number of farms | Manual | Combine | Mean | Manual | Combine | Mean |
| Y1 WS | 8 | 4130 | 4090 | 4110 | 2.5 | 5.3 | 3.9 |
| Y1 DS | 2 | 4840 | 4930 | 4890 | 4.5 | 5.6 | 5.0 |
| Y2 WS | 8 | 3660 | 3640 | 3650 | 2.5 | 4.2 | 3.4 |
| Y2 DS | 2 | 4930 | 4990 | 4960 | 2.5 | 5.7 | 4.1 |
| Mean | 20 | 4090 | 4090 | 4090 | 2.7 | 4.9 | 3.8 |
| LSD at 5% (HM) | | | | ns | | | 0.2** |
| LSD at 5% (F) | | | | 182** | | | 0.6** |
| LSD at5% (HM × F) | | | | ns | | | 0.9** |
| | | Moisture content (%wb) | | | Fissured grain (%) | | |
| Season | Number of farms | Manual | Combine | Mean | Manual | Combine | Mean |
| Y1 WS | 8 | 22.5 | 22.7 | 22.6 | 11.0 | 11.0 | 11.0 |
| Y1 DS | 2 | 24.2 | 24.2 | 24.2 | 15.0 | 14.5 | 14.8 |
| Y2 WS | 8 | 23.6 | 23.5 | 23.5 | 7.5 | 10.0 | 8.8 |
| Y2 DS | 2 | 25.2 | 25.1 | 25.1 | 1.7 | 2.8 | 2.3 |
| Mean | 20 | 23.4 | 23.4 | 23.4 | 9.1 | 10.2 | 9.6 |
| LSD at 5% (HM) | | | | ns | | | 0.9** |
| LSD at 5% (F) | | | | 1.0** | | | 2.9** |
| LSD at 5% (HM × F) | | | | ns | | | 4.0** |

HM: Harvest method; F: farm; ns: not significant. $^{**}p < 0.01$.
Mean values for each season and all 4 seasons are also shown.

1.3% to 25% and from 2.5% to 19.3% in manual and combine harvesting, respectively. While fissured grain under manual and combine harvesting was strongly correlated to each other ($r$ = 0.73**, $n$ = 20), it was on average slightly higher in combine harvested crops than in manual harvested crops. There was also a significant interaction between harvesting method and farmer; manual harvesting caused greater fissuring when grain moisture content was low, but this was not the case when it was high.

When data from combine and manual harvesting across 20 farms were considered together, there was a significant negative correlation between fissured grain and grain moisture content (Figure 1). Thus, when grain moisture content was 25% or higher, fissured grain was mostly less than 15%. On the other hand, fissured grain of 20% or higher was obtained when the grain moisture content was below 23%.

Observation of commercial combine harvesting operation in 20 fields in Experiment 1 provided opportunity to determine time required for combine to harvest rice crops and record the number of people to run the whole operation and compare this to the manual harvesting operation (Table 4). Combine fee charge varied depending on season and crop condition such as lodging in the paddy field, but we used the average price of USD100/ha. The operation takes 3 h to complete the harvest of 1 ha of rice, and it required two workers. The labour cost was USD10/8 h for cleaning, and hence the total cost for combine harvesting was USD110/ha, and the time spent in the field was 11 h. The rice grain harvested manually needed 4 different processes to complete the task, and the labour requirement was 37 man-days and a total of 25 h. The total cost was USD185/ha and spend 25 h.

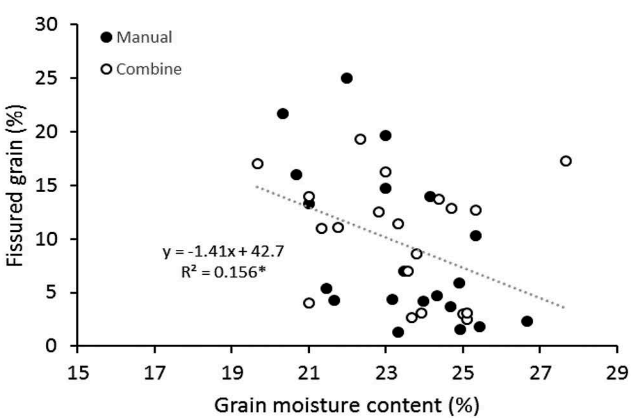


**Figure 1.** Relationship between fissured grain (%) and grain moisture content (%wb) for rice crops harvested manually or by combine in 20 farms in Takeo, Cambodia.

**Table 4.** Estimation of cost, time and labour required for each operation for combine harvesting and manual harvesting (USD/ha).

| | | Combine harvester | | Manual harvesting | | |
|---|---|---|---|---|---|---|
| No. | Activity | Unit price (USD/ha) | Time (hour) | Labour required | Time (hour) | Unit price (USD/person/day) |
| 1 | Harvesting | 100 | 3 | 25 | 8 | 5 |
| 2 | Field collection | 0 | 0 | 5 | 5 | 5 |
| 3 | Threshing | 0 | 0 | 5 | 4 | 5 |
| 4 | Cleaning | 10 | 8 | 2 | 8 | 5 |
| | Total | 110 | 11 | 37 | 25 | 185 |

### 3.2. Experiments 2 and 3: grain yield, grain harvesting loss and milling quality of crops harvested manually or by combine at different ripening stages

In 2016 (Experiment 2), grain moisture was high at 24.9% at 25 DAF and decreased slightly to 23.0% at 30 days and then reduced sharply as harvesting was delayed to 35 DAF (Table 5). However, there was no significant effect of harvesting method nor harvesting method by harvesting time interaction effect. Grain harvesting loss was greater when harvested by combine than manually, and harvesting at 30 DAF resulted in slightly lower loss than the other times. Fissured grain more than doubled when harvesting was delayed from 25 to 30 DAF. The result in 2017 (Experiment 3) was similar to that obtained in 2016; grain moisture decreased and fissured grain increased with delay in harvesting. However, the grain yield was highest at 25 DAF and fissured grain was generally smaller in 2017. In 2017, grain maturity was not uniform judging from the colour of grains, and also the crop was affected by stem borer.

In both 2016 and 2017, milling quality was not significantly affected by harvesting method or harvesting time (Table 6). In 2016, mean brown rice was 73.8%, white rice 64.6% and head rice 39.0%, while in 2017, mean brown rice was 75.7%, white rice 64.4% and head rice 41.6%. Thus, despite similar white rice percentage, mean HRY was slightly greater in 2017 than in 2016.

### 3.3. Changes in grain moisture content, fissured grain and HRY during ripening in four seasons (2014–2017)

Grain moisture content, fissured grain and HRY varied only slightly between combine and manual harvesting, and hence mean values obtained at different harvesting times in 2014–2017 are shown in Table 7. Grain moisture content was about 25–28%wb at 25 DAF in all years and declined during ripening. The decline was greatest in

**Table 5.** The effect of harvesting time (DAF, days after flowering) and method (HM, manual or combine) on rice grain moisture content (%wb), grain yield (kg/ha), grain loss (%) and fissured grain (%) for (a) Experiment 2 (2016) and (b) Experiment 3 (2017).

| Harvest time (DAF) | Moisture content (%wb) | | | Yield (kg/ha) | | | Grain loss (%) | | | Fissured grain (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (a) 2016 | Manual | Combine | Mean | Manual | Combine | Mean | Manual | Combine | Mean | Manual | Combine | Mean |
| 25 | 24.7 | 25.1 | 24.9 | 4670 | 4290 | 4480 | 1.3 | 3.1 | 2.2 | 19.2 | 14.5 | 16.9 |
| 30 | 23.9 | 22 | 23 | 4790 | 4570 | 4680 | 1.3 | 2 | 1.6 | 37.4 | 32.3 | 34.8 |
| 35 | 18.6 | 18.8 | 18.7 | 4620 | 4310 | 4470 | 1.6 | 2.6 | 2.1 | 43.5 | 41.1 | 42.3 |
| Mean | 22.4 | 22 | 22.2 | 4690 | 4390 | 4540 | 1.4 | 2.6 | 2 | 33.4 | 29.3 | 31.3 |
| LSD 5% (HM) | | | ns | | | 235* | | | 0.2** | | | ns |
| LSD 5% (DAF) | | | 1.1** | | | ns | | | 0.3* | | | 6.6** |
| LSD 5% (HM × DAF) | | | ns | | | ns | | | 0.4* | | | ns |
| (b) 2017 | | | | | | | | | | | | |
| 25 | 25.8 | 25.8 | 25.8 | 3600 | 3670 | 3630 | 1.4 | 2.5 | 1.9 | 10.1 | 6.4 | 8.3 |
| 30 | 22.5 | 23 | 22.8 | 3260 | 3280 | 3270 | 3 | 3 | 3 | 14.2 | 10.3 | 12.3 |
| 35 | 16.1 | 15.8 | 16 | 3340 | 3270 | 3310 | 3.3 | 3.7 | 3.5 | 27.4 | 19 | 23.2 |
| Mean | 21.5 | 21.5 | 21.5 | 3400 | 3410 | 3400 | 2.6 | 3.1 | 2.8 | 17.2 | 11.9 | 14.6 |
| LSD 5% (HM) | | | ns | | | ns | | | 0.3** | | | 2.0** |
| LSD 5% (DAF) | | | 0.7** | | | 152** | | | 0.3** | | | 2.5** |
| LSD 5% (HM × DAF) | | | ns | | | ns | | | 0.4* | | | ns |

HM: Harvest method; DAF: days after flowering; ns: not significant. $*p < 0.05$; $**p < 0.01$.

**Table 6.** The effect of harvesting time (DAF, days after flowering) and method (HM, manual or combine) on brown rice (%), white rice (%) and head rice (%) for (a) Experiment 2 (2016) and (b) Experiment 3 (2017).

| Harvest time (DAF) | Brown rice (%) | White rice (%) | Head rice yield (%) |
|---|---|---|---|
| (a) 2016 | | | |
| 25 | 73.7 | 64.3 | 38.2 |
| 30 | 74.0 | 65.2 | 41.6 |
| 35 | 73.9 | 64.4 | 37.3 |
| Mean | 73.8 | 64.6 | 39.0 |
| LSD 5% (HM) | ns | ns | ns |
| LSD 5% (DAF) | ns | ns | ns |
| LSD 5% (HM × DAF) | ns | ns | ns |
| (b) 2017 | | | |
| 25 | 75.0 | 63.9 | 39.1 |
| 30 | 75.8 | 63.3 | 43.3 |
| 35 | 76.3 | 66.1 | 42.4 |
| Mean | 75.7 | 64.4 | 41.6 |
| LSD 5% (HM) | ns | ns | ns |
| LSD 5% (DAF) | ns | ns | ns |
| LSD 5% (HM × DAF) | ns | ns | ns |

HM: Harvest method; DAF: days after flowering; ns: not significant.

**Table 7.** Grain moisture content, fissured grain and head rice yield (HRY) of rice crops harvested between 25 and 45 days after flowering (DAF) in 2014–2017.

| | Harvest time (DAF) | 2014 | 2015 | 2016 | 2017 |
|---|---|---|---|---|---|
| Grain moisture content (%wb) | 25 | 26.9 | 27.7 | 24.9 | 25.8 |
| | 30 | – | – | 23 | 22.8 |
| | 35 | 24.7 | 24.2 | 18.7 | 16 |
| | 45 | 18.1 | 14.9 | – | – |
| Fissured grain (%) | 25 | 8.5 | 18.3 | 16.9 | 8.3 |
| | 30 | – | – | 34.8 | 12.3 |
| | 35 | 43.5 | 54.5 | 42.3 | 23.2 |
| | 45 | 84.5 | 87.7 | – | – |
| Head rice yield (%) | 25 | 44.3 | 43 | 38.3 | 39.2 |
| | 30 | – | – | 41.6 | 43.4 |
| | 35 | 33.2 | 29.5 | 37.3 | 42.4 |
| | 45 | 9.5 | 17 | – | – |

Values are means of manual and combine harvesting.

2017 when the moisture content declined to 16%wb at 35 DAF. Fissured grain at harvest was 8–18% at 25 DAF and increased sharply. However, the increase was slower in 2017 when fissured grain only reached to 23% at 35 DAF. HRY was 38–44% when harvesting took place at 25–30 DAF. HRY declined by 35 DAF in the first 2 years, but it was still relatively high at 42.4% in 2017.

When mean value of each treatment combination (harvest time × harvest method × year) was considered, low HRY <20% was obtained when moisture content was below 20%wb (Figure 2(a)). When grain moisture content exceeded 27%wb, HRY was close to maximum treatment mean of 45%. A significant correlation existed between HRY and grain moisture content ($r$ = 0.54**, $n$ = 24). Despite this however, there was large variation in HRY for a given moisture, for example grain moisture content was 15–17%wb at 45 DAF and HRY was below 20%, while at a similar moisture content at 35 DAF in 2017, HRY exceeded 40%. On these occasions, fissured grain was rather small, and thus HRY was strongly related to fissured grain at harvest (Figure 2(b)). Thus, HRY of around 45% was often obtained when fissured grain was less than 20%, although similarly high HRY may be obtained with fissured grain close to 40% as was the case for crops harvested at 35 DAF in 2016. Fissured grain was generally lower when the harvested grain had higher moisture content, and it was less than 25% when the moisture content exceeded 26%wb (Figure 2(c)).

Daily mean accumulated temperature between 50% flowering and harvest was positively associated ($r$ = 0.94**, $n$ = 24) with fissured grain and negatively associated with HRY (Figure 2(a); $r$ = −0.85**, $n$ = 24) and grain moisture content ($r$ = 0.79**, $n$ = 24).

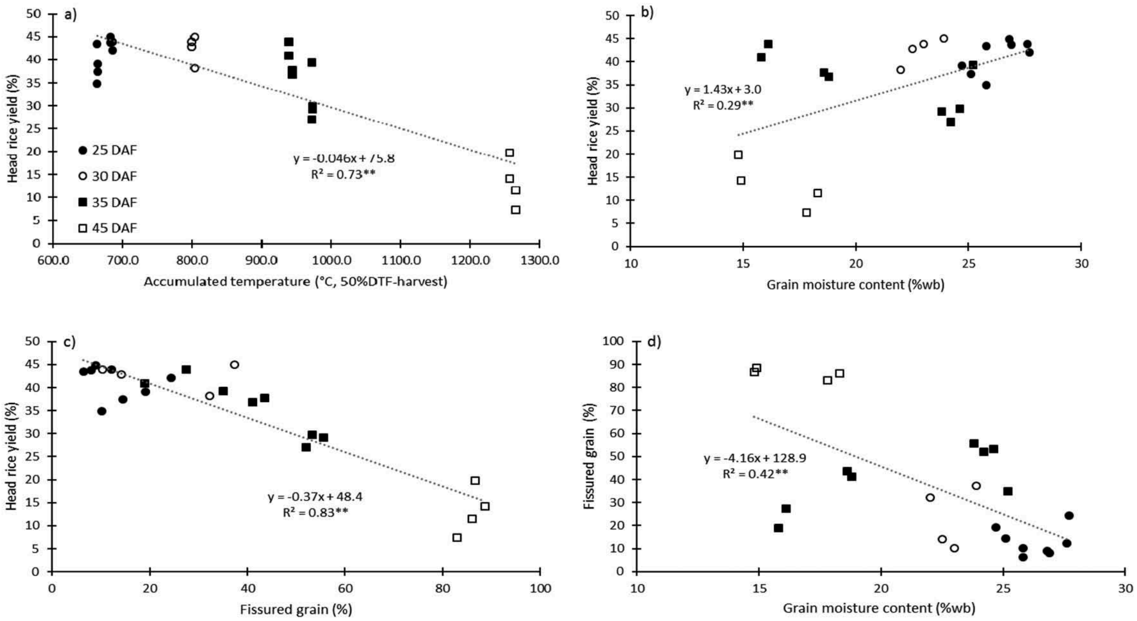


**Figure 2.** Relationship between head rice yield and (a) accumulated temperature (°C, from 50% flowering to harvest); (b) grain moisture content (%wb); (c) fissured grain and (d) between fissured grain and moisture content (%wb), for crops harvested manually or by combine at different times during ripening in 2014–2017.

### 3.4. Mill study

The moisture content at delivery was high at around 29%wb in all mills (Table 8), possibly due to the use of sacks for transportation to the mills. Moisture content decreased to around 14%wb after drying and slightly further after whitening. Fissured grain was around 5–6% at delivery in all mills but increased sharply after drying in Mill B and Mill C and during storage in Mill A and Mill C. After milling, there were some broken rice but around 90% of brown rice were not broken in all mills. Fissured grain of these head brown rice was about 10%. After polishing, 70–80% of white rice was head rice and 20–30% broken. In these white head rice, 10–15% was fissured.

## 4. Discussion

The research station experiments in 2014–2017 showed that fissured grain was generally lower when grain moisture content at harvest was high. The research station results were also confirmed in 20 farmers' fields. Experiment 1 showed that the grain moisture content was mostly above 20%wb and fissured grain was less than 25% among 20 farms examined, but fissured grain was mostly less than 15% when grain moisture content was around 25%wb. The relationship between HRY and moisture content and also fissured grain found in the research station results suggests that HRY close to maximum was likely to be obtained with grain moisture content greater than 25%wb and fissured grain of less

**Table 8.** The change in grain moisture content (%), fissured grain (%) and whole grain (%) at five different stages in three rice mills and the mean and standard error (±) across mills in Phnom Penh area.

| | Before drying | After drying | After storage | Brown rice | White rice |
|---|---|---|---|---|---|
| (a) Moisture content (%wb) | | | | | |
| Mill A | 28.5 | 14.8 | 14 | 15.3 | 13.8 |
| Mill B | 28.7 | 14.2 | 14 | 13.6 | 13.1 |
| Mill C | 29.3 | 14.1 | 14.1 | 13.1 | 12.4 |
| Mean | 28.8 ± 0.14 | 14.3 ± 0.12 | 14.1 ± 0.01 | 14 ± 0.38 | 13.1 ± 0.23 |
| (b) Fissured grain (%)+ | | | | | |
| Mill A | 4.7 | 4.6 | 13.8 | 8.3 | 9.7 |
| Mill B | 6.2 | 19.1 | 20.3 | 8.4 | 14.8 |
| Mill C | 5.8 | 12.9 | 20.1 | 13.3 | 12.8 |
| Mean | 5.6 ± 0.27 | 12.2 ± 2.42 | 18.1 ± 1.24 | 10 ± 0.95 | 12.4 ± 0.86 |
| (c) Whole grain (%) | | | | | |
| Mill A | | | | 92.7 | 81.6 |
| Mill B | | | | 87.6 | 80.8 |
| Mill C | | | | 88.1 | 72 |
| Mean | | | | 89.5 ± 0.94 | 78.1 ± 1.78 |

+Fissured grain (%) for brown and white rice was determined as percentage of whole grain.

than 15%. Thus, it appears, combine operators were able to harvest rice at appropriate times to achieve maximum HRY. In rice mills in southern Cambodia, they prefer to receive grain with moisture content of 25–26%wb, and this practice is in accordance with the findings of the present results of the field and research station experiments. However, when grain was harvested too early, grain moisture content of higher than 27%wb may be obtained. Earlier work has shown that high moisture content rice did not have appropriate texture and bright white colour and had high chalkiness score, and when milled, the white rice was reduced by 2% (CARDI, 2006–09). These early harvests may contain a high proportion of immature grain, and the mill may pay less with such high moisture paddy. In addition, there is the cost associated with drying extra-moist grain (Siebenmorgen et al., 2008). The optimum moisture content found in southern Cambodia was higher than that reported from USA of around 21%wb in Arkansas (Siebenmorgen et al., 2013), and 16–23%wb in Texas (Calderwood et al. 1980).

However, the results also show rather large variation in HRY at around 25%wb grain moisture content and also that high HRY could be obtained with low moisture content below 20%wb. For example at 35 DAF in 2017, grain moisture content was only 16%wb but high HRY exceeding 42% was achieved. This was related to the fact that fissured grain was low in that harvest. Thus, the present study results confirm our previous finding that grain moisture content at harvest was not reliable indicator of HRY in southern Cambodia (Bunna et al., 2018). Environmental conditions during late grain filling may affect the fissured grain and subsequently broken rice and HRY, and temperature may have played some role in the present work. The mean temperature for 15 days prior to harvest was around 1°C cooler in 2017 than earlier years. It may be that the cool period coincided with late ripening phase reduced fissured grain leading to higher HRY. The importance of mean temperature prior to harvesting was reported by Abayawickrama (2018). Of the various temperature parameters, the accumulated temperature between 50% flowering and harvest had the strongest relationship with increased fissured grain and reduced HRY. While high night-time temperature was also found to adversely affect HRY (Lanning et al., 2011), the night-time temperature variation across 4 years in the present study was not related to HRY. In addition to direct environmental effects, the plant's ability to fill grain may affect grain fissures and subsequently HRY. On the other hand, the grain maturity in 2017 was not uniform due to high incidence of stem borer, and this may have affected sink–source relationship affecting development of fissured grain. Growing seasons and nitrogen application rate are known to affect HRY (Zhou et al., 2015).

Thus, the results of 4 years' research station experiments in 2014–2017 show that HRY was more strongly related to fissured grain than moisture content, and some variation in HRY for a given moisture content may be related to the fissured grain at the time of harvesting. The importance of fissured grain at harvest in determining HRY confirmed earlier studies not only on harvest time (Bunna et al., 2018; Siebenmorgen et al., 2007) but also on year-to-year fluctuation. The physiological mechanisms determining fissured grain require further research.

While the results of Experiments 2 and 3 show no significant variation in HRY of crops harvested between 25 and 35 DAF, results across four seasons indicated that maximum HRY would be obtained if crops were harvested around 25–30 DAF. While determination of flowering time may not be practical currently, the advance in remote sensing would enable the recording of flowering time for individual paddy fields, and the new technology would help identify optimum harvesting time. As the grain ripens quickly in tropical environments, coordination of combine operators to harvest crops in a timely manner is required for maintaining high-quality product.

The mill study showed high initial grain moisture content, which was probably related to the use of plastic sacks for transportation from the field to the mill. The change in moisture content may induce grain fissures although grain fissure percentage was low at about 5% when the harvested rough rice was delivered to the mills in the present study. As the proportions of husk and bran were not determined in the mill study, HRY could not be calculated. However, the percentage of head grain, i.e. unbroken grain percentage in white rice, was 72–82%, which was higher than the head grain percentage obtained in the research station study. The lower fissured grain at delivery and possibly superior artificial drying method may be responsible for such results in the mill study. Artificial drying often produced higher HRY than sun drying (Xangsayasane, Phongchanmisai, Bounphanousay, & Fukai, 2019).

The present study showed that grain loss in the field was higher with combine harvesting than with manual harvesting. However, manual harvesting incurs further grain losses during the additional processes required with manually harvested crops e.g. collection of panicles from the field and threshing, the addition of which results in a similar total grain loss as combine harvesting, as noted by Bunna et al. (2018). Grain yield was similar between the two harvest methods. In addition combine harvesting also produced fissured grain and HRY that were similar to those of manual harvesting. Similar points were noted in the comparison of combine and manual harvesting in Laos (Vongxayya et al., 2019). Thus, combine and manual harvesting would produce similar grain yield and hence income. However, the present study also has shown that the cost of harvesting would be cheaper with combine harvesting. Thus, the comparison of net income between combine contracting and manual harvesting shows substantial benefit to farmers with the adoption of combine harvesting. The combine harvesting contracting fees are generally higher in wet season crops as they tend to lodge and require longer time to harvest. The costs of both combine and manual harvesting estimated here are generally cheaper than those estimated for Laos by Xangsayasane et al. (2019a). This is likely because the combine harvesting is efficient and the business is competitive in Cambodia, and hence the fee charges have reduced. It is also likely that the areas that the combine has been introduced to in Laos have high labour cost, resulting in generally high cost of harvesting operations.

It is concluded that while grain moisture content at the time of harvesting may be used as an indication of subsequent HRY, the latter was more strongly related to fissured grain at harvest. Fissured grain at harvest leads to broken rice during the milling process, and harvest time during ripening and seasons were found to affect grain fissuring. Physiological research is required to determine factors other than moisture content that determine development of grain fissures prior to harvest.

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## References

Abayawickrama, A. S. M. T., Reinke, R. F., Fitzgerald, M. A., Harper, J. D. I., & Burrows, G. E. (2018) Influence of high daytime temperature during the grain filling stage on fissure formation in rice. *Journal of Cereal Science*, *74*, 256–262.

Bunna, S., Sereyvuth, H., Somaly, Y., Ngoy, N., Mengsry, L., Sareth, C, … Fukai, S. (2018). Head rice yield of crops harvested by combine and hand at different ripening times in Cambodia. *Experimental Agriculture*, 1–11.

Calderwood, D. L., Bollich, C. N., & Scott, J. E. (1980). Field drying of rough rice - effect on grain-yield, milling quality, and energy saved. *Agronomy Journal*, *72*(4), 649–653.

CARDI. (2006–09). Annual reports of Cambodian Agricultural Research and Development Institute, Phnom Penh, Cambodia.

Department of Agricultural Engineering. (2016). *Towards modernization and commercialization of cambodian agriculture. strategic development plan of agricultural engineering for Cambodia 2016–2020*. Phnom Penh, Cambodia: Author.

Lanning, S. B., Siebenmorgen, T. J., Counce, P. A., Ambardekara, A. A., & Mauromoustakos, A. (2011). Extreme nighttime air temperatures in 2010 impact rice chalkiness and milling quality. *Field Crops Research*, *124*(1), 132–136. Retrieved from <Go to ISI>://WOS:000296595800014.

Meas, P., Paterson, A. H. J., Cleland, D. J., Bronlund, J. E., Mawson, A. J., Hardacre, A., & Rickman, J. F. (2011). Effects of different solar drying methods on drying time and rice grain quality. *International Journal of Food Engineering*, *7*(5). Retrieved from <Go to ISI>://WOS:000295515700009. doi:10.2202/1556-3758.2378.

NAPHIRE. (1997). *National postharvest institute for research and extension-technical guide on grain postharvest operation*. Muñoz, Nueva Ecija, Philippines: Author.

Siebenmorgen, T. J., Grigg, B. C., & Lanning, S. B. (2013). Impacts of preharvest factors during kernel development on rice quality and functionality. In M. P. Doyle & T. R. Klaenhammer (Eds.), *Annual Review of Food Science and Technology* (Vol. 4, pp. 101–115). doi:10.1146/annurev-food-030212-182644

Siebenmorgen, T. J., Bautista, R. C., & Counce, P. A. (2007). Optimal harvest moisture contents for maximizing milling quality of longand medium-grain rice cultivars. *Applied Engineering in Agriculture*, *23*(4), 517–527. Retrieved from <Go to ISI>://WOS:000248928500015.

Siebenmorgen, T. J., Cooper, N. T. W., Bautista, R. C., Counce, P. A., Wailes, E., & Watkins, K. B. (2008). Estimating the economic value of rice (Oryza sativa L.) as a function of harvest moisture content. *Applied Engineering in Agriculture*, *24*(3), 359–369. Retrieved from <Go to ISI>://WOS:000256553200011

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. Retrieved from <Go to ISI>://WOS:000238596400012.

Vongxayya, K, Jothityangkoon, D, Ketthaisong, D, Mitchell, J, Xangsayyasane, P, & Fukai, S. (2019). Effects of introduction of combine harvester and flatbed dryer on milling quality of three glutinous rice varieties in lao pdr. *Plant Production Science*, *22*(1), 77–87.

Xangsayasane, P, Phongchanmisai, S, Bounphanousay, C, & Fukai, S. (2019a). *Combine harvesting efficiency as affected by rice field size and other factors and its implication for adoption of combine contracting service*. *Plant Production Science*, *22*(1), 68–76.

Xangsayasane, P., Vongsaiya, K., Phongchanmisai, S., Mitchell, J. H., & Fukai, S. (2019b). Rice milling quality as affected by drying method and harvesting time during ripening in wet and dry seasons. Plant Production Science, 22(1), 98-106.

Zhou, L. J., Liang, S. S., Ponce, K., Marundon, S., Ye, G. Y., & Zhao, X. Q., (2015). Factors affecting head rice yield and chalkiness in indica rice. *Field Crops Research*, *172*, 1–10. Retrieved from <Go to ISI>://WOS:000349506600001.