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Increased rate of potassium fertilizer at the time of heading enhances the quality of direct seeded rice

Anjana J. Atapattu[1,2,3], B. D. Rohitha Prasantha[4*], K. S. P. Amaratunga[5] and Buddhi Marambe[6]

Abstract

Background: Potassium (K) is not easily assimilated into organic matter but helps to improve rice quality. Paddy yield and its quality depend on the correct time of fertilization and harvesting (days after flowering) in the field.

Methods: Changes in the grain quality of (*Oryza sativa* L.) were studied in a field experiment over two dry seasons using three rates of muriate of potash (MOP; 60% K_2O) as 12.5, 25 and 37.5 kg/ha applied at the time of heading (7 weeks after planting—WAP). Paddy samples were harvested during 25, 30 (control), 35 and 40 days after 50% flowering (DAFF). Grain yield and physico-chemical characteristics of grain were studied after harvesting.

Results: The impact of seasons and treatments' interactions was not statistically significant ($P > 0.05$) and, hence, data were averaged over two seasons. Length, breadth, true density and bulk density of rice grains were the highest with 37.5 kg MOP/ha applied at heading and harvested at 30–35 DAFF. Crude protein (6.24%) and crude fat (2.61%) contents in grains were the highest when harvested at 40 DAFF and 35–40 DAFF, respectively. Amylose content decreased with increased MOP rates at the time of heading and delayed paddy harvest. The highest average paddy yield (APY; 6.85 t/ha), head rice yield (HRY; 65%) and total rice milling yield (TMY; 67%) were recorded with 37.5 kg MOP/ha applied at heading of rice plant and paddy harvested at 35 DAFF. The APY, HRY and TMY were also 13.8, 7.7 and 5.9% higher, respectively, compared to the control. Applying K fertilizer at a rate 50% more (18.75 kg K/ha) than the recommended rate at the time of heading (7 WAP) and harvesting paddy at optimum maturity (35 DAFF), which is 5 days later than the recommendation, increase the yield and grain quality of direct seeded rice. Harvesting later than 35 DAFF resulted in a 10.5% loss of HRY ($P < 0.05$).

Conclusions: The present study showed that K fertilizer applied at the rate of 37.5 kg MOP/ha at the time of heading 50% higher than the recommended rate is the best among K fertilizer treatments to obtain the highest HRY.

Keywords: Grain quality, Potassium, Time of heading, Harvesting, Milling yield, Paddy, Head rice yield

Background

Paddy (*Oryza sativa* L) is mostly cultivated as a direct seeded crop in Sri Lanka and the annual production is approximately 4.6 million tons resulting in a surplus of rice (de-husked paddy) since 2009 [1]. The annual per capita consumption of rice in Sri Lanka is approximately 116 kg. Expanding cultivation area and adoption of new high yielding varieties are the major causes for increased productivity. Although increasing the achievable yield from new paddy cultivars is critical for sustainable production, processing and cooking quality of rice has now become important as it determines the acceptability of rice for both export and domestic markets. Changing major agronomic practices such as irrigation, fertilization and harvesting at the correct time are important since they are strongly associated with cooking and processing quality of rice [2].

*Correspondence: bdrp@pdn.ac.lk
[4] Department of Food Science & Technology, Faculty of Agriculture, University of Peradeniya, Peradeniya 20400, Sri Lanka
Full list of author information is available at the end of the article

Field crops generally absorb potassium (K) faster than nitrogen (N) or phosphorous (P), where K also plays an important role in ensuring efficient utilization of N [2]. Potassium is not easily assimilated into organic matter as in the case of N and P, but helps in translocation of photosynthetic products and other plant metabolites, thus contributing to improved grain quality [3, 4]. Though K is not a constituent of any plant structure or compound, K input plays a role in many important regulatory processes in the plant such as the grain quality of rice [5]. Rice and wheat require large quantities of K, and a continuous supply of K is necessary up to heading stage after completion of the reproduction stage [2, 6]. It was shown that 200–300 kg K_2O/ha is necessary to obtain 5–10 t/ha of cereal crop yield [7]. Previously studies have also reported that higher K rates result in a stronger aroma, whiter and glassier appearance and lower softness in basmati rice [8]. Potassium fertilization applied as panicle-fertilizer significantly increases the grain yield and quality [9].

Grain yield and its quality depend on the correct judgment on harvesting. Therefore, correct timing of harvesting is important to obtain a higher milling yield with good quality grains [10] fetching higher value for the production in domestic and foreign markets in Europe and Middle East countries. The optimum time for harvesting may be specified by days after flowering of rice panicle [11]. In Sri Lanka, paddy is generally harvested when 80–85% of the panicles turns into yellow-straw color, which is approximately 30–34 days after completion of flowering [12]. Moisture content at this stage is about 20–22%. Allowing the crop to stand in the field after reaching optimum maturity would reduce the percentage of head rice recovery at milling. Postharvest losses of paddy associated with conventional harvesting and handling (before threshing) operations in the field could vary from 1 to 3% and 2 to 7%, respectively [13], amounting to approximately 0.12–0.4 million tons of the total annual production. Hence, determination of the optimum time for harvesting rice varieties is imperative to obtain higher yields and best grain quality. This study was initiated to identify the impact of different rates of K fertilizer application at the time of heading of rice plant and times of harvesting on the final yield and grain quality of rice.

Methods

Crop establishment and growth conditions

Field experiments were carried out during two cultivating seasons (*Yala* season; March to August) in subsequent years, at the seed farm of the CIC Agri Businesses Private Limited (http://www.cic.lk). The experimental site was located in the agro-ecological region "Low Country Dry Zone (LD)" of Sri Lanka (7°30′ N and 80° 50′ E). The minimum night temperature of the site varied from 26 to 28 °C and the maximum day temperature was in the range of 30–33 °C during the cultivating season of both years. The annual rainfall ranged from 1060 mm to 1805 mm. The soil was a low humic glay with an average pH of 5.7 at 0–20 cm depth. The average soil nutrient composition was 14 kg N, 709 kg P_2O_5, 215 kg K_2O, 5.4 kg Zn, and 297 kg Mg per hectare, with approximately 1.4% organic matter. Certified seed paddy (*Oryza sativa* L) variety CIC 300 obtained from "CIC Agri Businesses" was used for this experiment in both seasons. The paddy variety CIC 300, which matures approximately within 3 months, is with low shattering panicles, red pericarp, and long-grain shape known as basmati type. The variety is produced mainly for the export market requirement.

After land preparation, the experimental area was demarcated by plots at a size of 5 m × 4 m using bunds of 0.35 m width and 0.4 m height. The water outlets of plots were prepared ensuring that the drained water will not enter through an inlet of another plot. Pre-germinated seeds of rice were broadcasted as direct seeded rice at the rate of 100 kg/ha while soil moisture was at the field capacity. The total experimental area was about 2000 m^2 (0.2 ha). Irrigation, fertilization and other management practices were done according to the recommendations of the Department of Agriculture (DOA), Sri Lanka (http://www.agridept.gov.lk/), except for potassium fertilizer treatments and time of harvesting.

The crop production package for the paddy variety CIC 300 included the fertilizer recommendation made by the DOA for a rice crop grown in the LD with an average yield of 5 t/ha [14]. The DOA [14] recommended the application of a pre-plant, basal fertilizer mixture comprising urea (46% N): triple super phosphate (TSP; 46% P_2O_5): muriate of potash (MOP; 60% K_2O) in a ratio of 12.5:62.5:37.5 (kg/ha, w/w/w). As the first and second top dressings, urea was applied 2 and 5 weeks after planting (WAP) at 62.5 kg/ha and 100 kg/ha, respectively.

A mixture of 50 kg/ha of urea and 25 kg/ha of MOP was applied 7 WAP (time of heading) as recommended by the DOA. The rate of MOP applied 7 WAP was varied in this experiment as follows: as potassium (K) fertilizer supplement at the time of heading was considered the critical time of heading in rice, three levels of MOP applications at the time of heading were evaluated in this study, namely 12.5 kg MOP/ha (≈6.25 kg K/ha), 25 kg MOP/ha (≈12.5 kg K/ha) and 37.5 kg MOP/ha (≈18.75 kg K/ha). The treatment 25 kg MOP/ha served as the control (recommendation made by the DOA for about 20 years).

The paddy yield was harvested at four different maturity periods (harvesting ages) at 25 days after 50% flowering (DAFF), 30 DAFF, 35 DAFF and 40 DAFF, at each level of MOP application. In the present study, the rice variety reached 50% flowering stage in about 66 days after planting in both seasons (years). Many rice varieties in Sri Lanka complete flowering after 2–3 days from reaching the 50% flowering stage. A previous study had identified the correct time for paddy harvest as 30–34 days of post-completion of flowering [12]. Hence, in the present study, 30 DAFF was considered as the control based on the recommendation of the DOA as the optimum time to harvest paddy in Sri Lanka.

Sampling

Samples were collected using a 2 m × 2 m quadrant placed at the center of plots and the plants were harvested manually. Threshing was done manually by stripping off the grains from the panicle. All paddy samples were sun dried to have approximately 13% moisture (wet basis). The samples were packed in perforated polypropylene sacks and kept at 10 °C until further analysis.

Grain quality and yield measurements

Paddy samples obtained from each treatment site (MOP × DAFF) were weighed to obtain the average paddy yield (APY). The true density of paddy (g/cm^3) and bulk density (g/cm^3) were determined according to the previous method described by Bhattacharya [15]. The gelatinization temperature (GT) value of the samples was measured by the alkali spreading value method [16, 17]. The milled rice samples were classified according to the size and shape classification of rice done by the International Rice Research Institute [18]. Fifty paddy grains were randomly picked from each sample and de-hulled with tweezers. The length (L, major axis) and breadth (B, intermediate axis) of brown rice kernels were measured by a micrometer screw gauge and L/B ratio was calculated [19]. The measurements were repeated 3 times for each sample.

Paddy samples of 150 g were hulled using a laboratory rubber roll Sheller (XXY155-Yanmar, Japan) and milled with a McGill rice miller (McGill mill No. 2 TX, USA). The broken rice grains were removed manually and also passing the milled rice through a sieve (2 mm). The milled rice kernels that had at least 2/3rd of the original kernel length were considered as head rice. The milling percentage of total milled rice yield (TMY) and head rice yield (HRY) recovery was determined as proposed by previous methods [20, 21]. The milled kernels were ground to flour in a laboratory scale grinder and passed through 80-mesh to obtain uniform particle size. Crude protein (CP %) and crude fat (CF %) contents were determined using the standard methods of analysis [17]. Apparent amylose content (AC %) of 100 mg rice flour sample (< 60 μm) was measured according to the AACC 61-03 method [17] using a UV–visible spectrometer (Jenway-6305, UK) at 620 nm.

Experimental design and statistical analysis

The experiment was arranged as a two-factor factorial in a randomized complete block design with three replicates. The MOP fertilizer rates, harvesting at different DAFF and their interactions were considered as fixed effects. The analysis of variance (ANOVA) was conducted using the SAS PROC GLM [22]. Initial tests were carried out to identify the effect of seasons and season x treatment interaction on the measured parameters. Treatment means were compared using Duncan's multiple range test (DMRT) at $P = 0.05$.

Results

The impact of cultivating seasons (two) and season x treatment interactions were not statistically significant ($P > 0.05$) for all the parameters evaluated. Hence, data for each parameter were averaged over two seasons and presented in this section.

Physical quality of rice

The results of the ANOVA carried out for the physical quality parameters of rice are presented in Table 1. The true density (TD) of paddy harvested did not show any significant interaction ($P > 0.05$) between K fertilizer rates and harvesting time. However, the TD significantly varied ($P < 0.05$) among the levels of each treatment (Table 1). The TD of rice grain increased and reached the maximum of 1.52 ± 1.51 g/cm^3 when paddy was harvested between 30 and 35 DAFF (Fig. 1), and decreased to 1.48 ± 0.005 g/cm^3 at 40 DAFF (P < 0.05). Increase in the level K fertilization at the time of heading (7 WAP) also increased the TD of rice ($P < 0.05$). The highest TD of 1.50 ± 0.003 g/cm^3 was observed at 37.5 kg MOP/ha applied at the time of heading. The bulk density (BD) of paddy also increased gradually but significantly ($P < 0.05$) with increased rate of K fertilizer at the time of heading and with delay of harvesting age. It reached its maximum at 35 DAFF (Table 2). The BD increased by about 8–10% with the rate of K fertilizer application higher than 12.5 kg/ha at the time of heading.

There was no significant interaction ($P > 0.05$) between the rate of K fertilizer at the time of heading and different harvesting times on grain dimensions. However, each treatment had a significant impact ($P < 0.05$; Table 1). The grain length (L) and breadth (B) increased significantly with application MOP fertilizer at rates greater than 25 kg/ha at the time of heading and increasing days taken to harvest from 30 DAFF. The highest L and B were detected at 37.5 kg MOP/ha applied at the time of heading and harvesting paddy

Table 1 ANOVA table of potassium fertilizer application at the time of heading and paddy harvest at different days after 50% flowering (DAFF) on the true density, bulk density, length, breadth, crude protein and crude fat of whole grain

Source of variation	df	*P* values*					
		True density	Bulk density	Length	Breadth	Crude protein	Crude fat
Block	2	0.054	0.87	0.82	0.65	0.050	0.08
K	2	0.001	0.001	0.02	0.02	0.01	< 0.0001
DAFF	3	< 0.0001	< 0.0001	< 0.0001	< 0.0001	0.04	< 0.0001
K × DAFF	6	0.78	0.72	0.27	0.81	0.96	0.051

K potassium fertilizer as muriate of potash (MOP), *DAFF* days after 50% flowering

* Significant effects that require means comparison $P < 0.05$

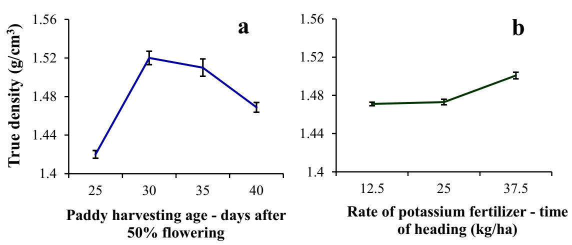

Fig. 1 Average true density of rice grains obtained from two cropping seasons; **a** when paddy was harvested at different days from 50% flowering and **b** application of different rates of muriate of potash at the time of heading. The vertical bars represent the standard error of the mean (30 DAFF and 25 kg MOP/ha were considered as controls)

approximately at 35 DAFF. The L/B ratio of the rice grain in all treatments was greater than 4 (Table 2) and the maximum of 4.43 was observed when K fertilizer was applied at 12.5 kg MOP/ha at the time of heading and paddy was harvested at 25 DAFF. The gelatinization temperature (GT) of the rice variety CIC 300 was 71.7 °C but showed no significant difference ($P > 0.05$) among all treatments combinations.

Proximate composition

The crude protein content (CP %), crude fat content (CF %) and amylose content (AC %) of rice grains did not show a significant interaction ($P > 0.05$) between the two treatments (Tables 1 and 3). The CP content increased significantly ($P < 0.05$) with increasing rate of MOP fertilizer at the time of heading of rice plant and age of paddy at harvesting (Table 4). The highest CP content recorded in this study was 6.24% with the application of 37.5 kg MOP/ha at the time of heading coupled with harvesting at 40 DAFF. The CF content was 3.3% higher when K fertilizer was supplied at the rate of 37.5 kg MOP/ha at the time of heading and 7.8% higher when paddy was harvested at 35–40 DAFF (Table 4) compared to the respective control (application of 25 kg MOP/ha of at the time of heading and harvesting paddy at 30 DAFF). The AC significantly decreased ($P < 0.05$) when the rate of MOP fertilizer applied at the time of heading was increased from 12.5 to 37.5 kg/ha and when harvest was delayed from 25 to 40 DAFF (Table 4).

Average paddy yield

The average paddy yield (APY) was influenced significantly by the interaction effect ($P < 0.05$) between the two treatments (Table 3; Fig. 2). At each K fertilizer level applied, the APY increased with the age of harvesting and recorded the highest yield of 6.85 Mt/ha at 35 DAFF, which was 13.8% higher than that recorded in the control plot (25 kg MOP/ha at the time of heading and harvesting paddy at 30 DAFF). Delaying paddy harvest beyond 35 DAFF showed a marginal decrease in the APY at all MOP levels applied at the time of heading.

Milled rice yield and head rice yield

A significant interaction between treatments was observed for milled rice ($P < 0.05$; Table 3). Figures 3 and 4 illustrate that delaying paddy harvest from 25 to 35 DAFF has resulted in a gradual increase in TMY and HRY across different rates of MOP applied at the time of heading and a significant decrease ($P < 0.05$) thereafter. At the lowest rate of K fertilizer applied at the time of heading (12.5 kg/ha) and early paddy harvest at 25 DAFF, the TMY of rice was the lowest. The highest TMY of 67% was obtained when MOP was applied at the rate of 37.5 kg/ha at the time of heading and the paddy was harvested at 35 DAFF, which was 6% higher than that observed in the control. The highest HRY of 65.3% was recorded from plots where paddy was harvested at 35 DAFF at the highest MOP level (37.5 kg/ha), which was 7.7% higher than the control. However, irrespective of the rate MOP fertilizer application at the time of heading, the HRY sharply decreased when paddy was harvested late at 40 DAFF. The results revealed that harvesting before 30 and after

Table 2 Physical grain quality parameters evaluated using different days of paddy harvest from 50% flowering and potassium fertilizer rates applied at the time of heading

Grain parameters	Harvesting age in days after 50% flowering (DAFF days)[d]				Rate of MOP applied at the time of heading (kg/ha)		
	25	30	35	40	12.5	25	37.5
Length (mm)	6.83 ± 0.04[a]	7.23 ± 0.05[b]	7.30 ± 0.06[b]	7.25 ± 0.05[b]	7.10 ± 0.02[a]	7.10 ± 0.01[a]	7.23 ± 0.02[b]
Breadth (mm)	1.54 ± 0.02[a]	1.73 ± 0.04[b]	1.73 ± 0.03[b]	1.74 ± 0.04[b]	1.65 ± 0.01[a]	1.70 ± 0.01[b]	1.75 ± 0.01[c]
L/B	4.43 ± 0.03[b]	4.18 ± 0.05[a]	4.22 ± 0.05[a]	4.16 ± 0.04[a]	4.30 ± 0.01[a]	4.18 ± 0.02[b]	4.13 ± 0.02[b]
BD (g/cm^3)	0.62 ± 0.01[a]	0.68 ± 0.01[b]	0.70 ± 0.02[b]	0.70 ± 0.01[b]	0.64 ± 0.01[a]	0.70 ± 0.01[b]	0.70 ± 0.01[b]

MOP muriate of potash (potassium fertilizer; 60% K_2O), *L/B* length to breadth ratio of the grain, *BD* bulk density of the rice grains

Mean (± SE) followed by the same superscript within a raw is not significantly different ($P > 0.05$) as measured by the DNMRT

[d] Data presented as mean ± SE

Table 3 The ANOVA table of rate of potassium fertilizer and paddy harvest at different days after 50% flowering on the amylose, average paddy yield, total milled rice and head rice yields of whole grain

Source of variation	df	*P* values*			
		Amylose	Average paddy yield	Total milled rice yield	Head rice yield
Block	2	0.96	0.48	0.85	0.20
K	2	0.015	0.014	0.042	0.047
DAFF	3	0.024	< 0.0001	< 0.0001	< 0.0001
K × DAFF	6	0.16	0.44	0.023	0.004

K potassium fertilizer as muriate of potash (MOP), *DAFF* days after 50% flowering

*Significant effects that require means comparison $P < 0.05$

Table 4 Proximate composition of rice grains when paddy was harvested at different days from 50% flowering and potassium fertilizer rates applied at the time of heading

Grain parameters	Harvesting age in days after 50% flowering (DAFF)[d]				Rate of MOP applied at the time of heading (kg/ha)[d]		
	25	30	35	40	12.5	25	37.5
Crude protein (%)	5.86 ± 0.05[a]	6.00 ± 0.05[ab]	6.18 ± 0.03[b]	6.24 ± 0.04[c]	5.87 ± 0.03[a]	6.08 ± 0.05[b]	6.24 ± 0.03[c]
Crude fat (%)	2.23 ± 0.05[a]	2.42 ± 0.06[b]	2.60 ± 0.06[c]	2.61 ± 0.07[c]	2.43 ± 0.04[a]	2.44 ± 0.06[a]	2.52 ± 0.07[a]
Amylose (%)	17.84 ± 0.4[c]	17.40 ± 0.3[b]	16.10 ± 0.4[a]	16.00 ± 0.3[a]	17.13 ± 0.4[b]	17.6 ± 0.4[b]	15.71 ± 0.2[a]

MOP muriate of potash (potassium fertilizer; 60% K_2O)

Mean (± SE) followed by the same superscript within a raw is not significantly different ($P > 0.05$) as measured by the DNMRT

[d] Data present as mean ± SE

35 DAFF would result in significantly lower ($P < 0.05$) HRY by 6.2% and 10.5%, respectively.

Discussion

Grain densities

The TD and BD are used to assess the level of grain filling with the maturity states of the rice [23]. The TD indicates the exact material density of the product itself. The increase observed in the TD and BD of rice grains at higher MOP rates applied at 7 WAP with delayed paddy harvest could be due to higher bulking of seeds during grain filling under optimum potassium fertilizer supplement given at the time of heading. Potassium is involved in the transportation of photosynthates from leaves to grain, thereby increasing the dry matter content of the plant and grain. Therefore, changing dry matter or moisture may significantly affect density. Bhattacharya et al. [24] reported that for every 1% increase in moisture or dry matter, the density of the paddy increased by about 7.5 kg/m^3. Thus, application of 37.5 kg MOP/ha at the time of heading and paddy harvested between 30 and 35

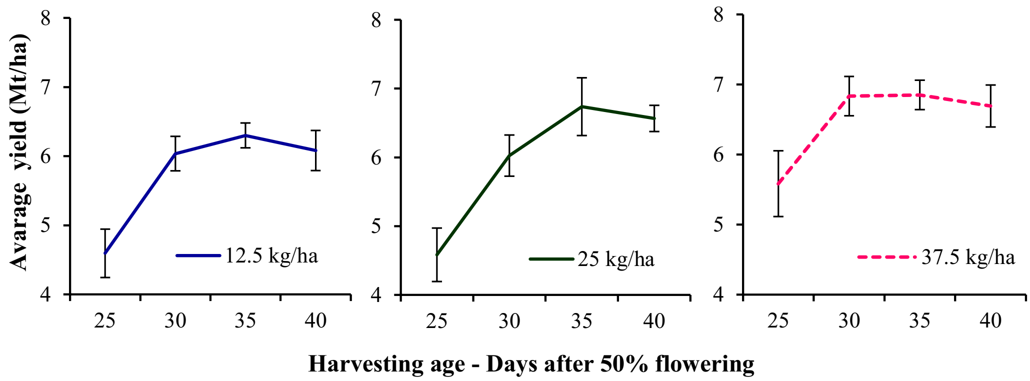

Fig. 2 Average paddy yield harvested at different days from 50% flowering under three rates of MOP fertilizer (kg/ha) applied at the time of heading of two cropping seasons. Vertical bars indicate the standard error of the mean (30 DAFF and 25 kg MOP/ha were the controls)

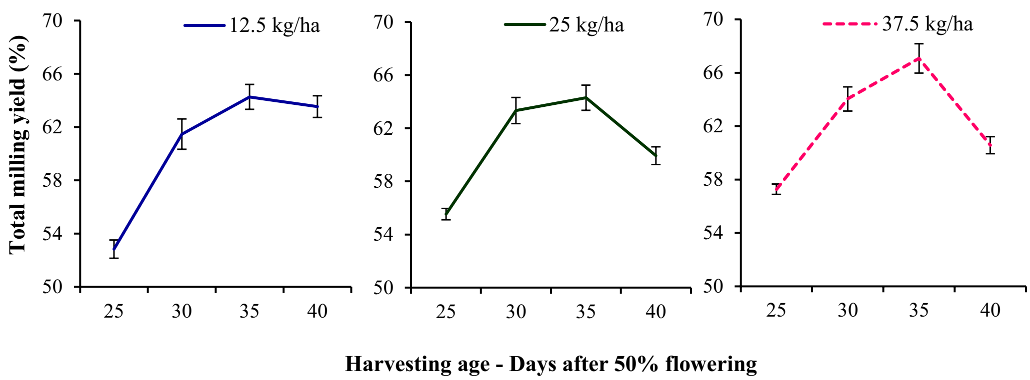

Fig. 3 Total milling yield of rice when paddy was harvested at different days from 50% flowering at three rates of MOP fertilizer applied (kg/ha) at the time of heading. Vertical bars indicate the standard error of the mean (30 DAFF and 25 kg MOP/ha were the controls)

DAFF could have contributed to the increase of dry matter content by about 6.7% and 12.6%, respectively.

Grain dimensions

Quality of rice grain is a complex character composed of many components such as nutritional, appearance, cooking and eating qualities [25]. Thus, the physical properties such as size, shape, uniformity, and general appearance are of utmost importance in determining the final milling quality of rice grains. The head grain dimensions are important when evaluating the rice grain quality as they show clear differences with time due to grain filling [26]. The longer kernel length and other physico-chemical properties were found to be distinctive features of the rice cultivars [27]. The grain L/B ratio of the rice grain in all treatments was greater than 3 (Table 2), which could be classified as 'slender' in shape [19, 27]. Basmati type rice varieties are longer and slender than typical long grain, often with an L/B ratio in the rage of 3.84–5.01 [19].

Gelatinization temperature

The results of the gelatinized temperature (GT) indicated the grains of the rice variety CIC 300 falls under the category high intermediate as described by [18]. This GT value is common for the majority of basmati type long grain rice varieties found in the world. Previous report showed that [28] application of K fertilizer did not affect the gelatinization temperature.

Proximate composition

The crude protein (CP) content of the internationally accepted premium basmati varieties varies between 7 and 9% [27]. Similar to the data obtained in this study. Another study [28] also reported that application of K fertilizer increased the grain protein content and gel consistency. According to previous findings, synthesis of

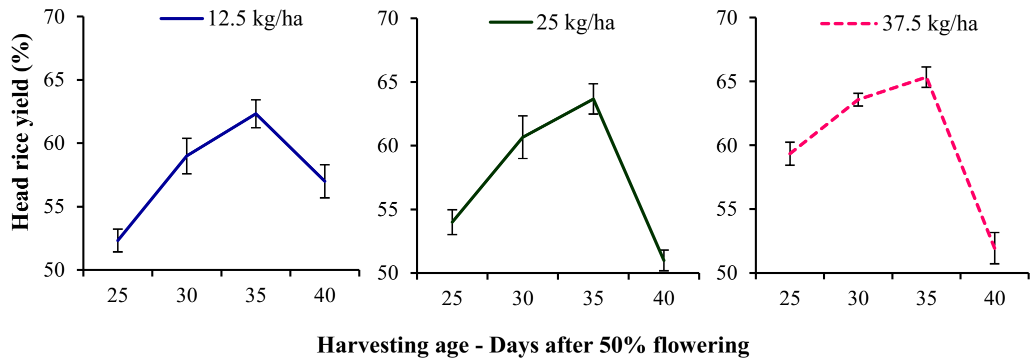

Fig. 4 Average head rice yield when paddy was harvested at different days from 50% flowering at three rates of MOP fertilizer applied (kg/ha) at the time of heading of two cropping seasons. Vertical bars indicate the standard error of the mean (30 DAFF and 25 kg MOP/ha were the controls)

protein is accelerated in the presence of adequate content of K [4, 9]. In the present study, the highest CP content (6.24%) recorded in the export rice variety CIC 300 (harvested at 40 DAFF) was marginally lower than the premium quality requirement for the international market. The maximum protein content in rice grain is accumulated 10 days after flowering [23, 29] and it decreases, however, with grain maturity up to 30–35 days after flowering of non-waxy rice [30]. However, low CP content in the rice grains was observed due to the accumulation of higher levels of amylose at harvesting at 25 DAFF across varying K fertilizer rates at the time of heading of rice plant [2, 9, 33].

Previous studies have reported that [27, 31] the CF content of paddy grains did not significantly differ between *japonica* and *indica* varieties but CF content varied between 2.0 and 3.2% in range. The CF content in the paddy grains in this study became low when paddy was harvested at 25 DAFF and at K fertilizer rate of 12.5 kg MOP/ha at the time of heading. This could be due to that paddy was harvested at an immature stage when the rice plant did not have enough time to translocate fat into the endosperm of seeds [23]. However, Choudhury and Juliano [32] reported that non-starch lipids in developing paddy grain get accumulated up to 16 days after flowering.

Rice with low amylose content (AC) has been reported to affect the eating and cooking qualities of cooked rice [31]. Previous studies have shown that AC increased in the paddy grain up to 20–21 days after flowering due to the activity of starch synthase and then decreased [29, 33]. The lowest AC in rice grains after 25 days flowering reported that AC became constant 30 days after flowering in non-waxy rice [30]. According to Hossain et al. [10], long grain aromatic rice harvested at 30–35 days after flowering was found to be the most suitable for higher head rice out-turn, elongation, volume expansion ratio and AC. It has been shown that the maximum AC can be obtained by application of K fertilizer at 180 kg K_2O/ha and 75 kg K_2O/ha with or without N fertilizer application, respectively [28, 33]. However, the present study found that the increasing rate of K fertilizer application from 12.5 to 37.5 kg MOP/ha at the time of heading reduced the AC significantly ($P < 0.05$) by about 8.3%. It is also important to note that soil of the experimental site contained an average of 215 kg of K/ha. Application of high level K fertilizer (MOP) at the time of heading together with N fertilizer at later growth stages (50 kg/ha of urea was added at the time of heading in the present study) or application of K fertilizer at late growth stage of paddy reduces the enzyme activity of starch synthase [33]. Liu et al. [5] showed that the grain filling regulatory enzyme activity is significantly reduced 20 days after heading and under K-deficient conditions. This could be the reason for decreasing amylose content reported with increasing K fertilizer rates applied at the time of heading and with delayed paddy harvest. The results highlight the importance of timing of K fertilizer application to support grain filling of rice plants.

Average paddy yield

It is well known fact that application of K fertilizer significantly increases the grain yield by about 47% with or without organic manure [34, 35]. Potassium deficiency reduces grain size and weight resulting in a direct yield loss if the grain does not respond to K fertilizer applications made after the growth stage of panicle differentiation [6]. According to a nano-material study, application of K as nano-K fertilizer at the rate of 20 kg K_2O/ha showed a significant increase in rice yield and number of seeds per panicle in direct seeded rice [36]. In the present study, the APY may also have decreased when harvested at 40 DAFF due to higher shattering, probably with the lowering of moisture content at the field or due to the source limitation to fulfill the sink demand. The same pattern was also observed with respect to TD of the rice grains. According to the previous reported data, an average agronomic response of 6 kg grain/kg of K for rice and wheat can be obtained by applying K fertilizer at the rate of 37.5 kg/ha [2]. The K uptake requirements for rice varieties that yield between 4 and 8 t/ha have ranged from 17 to 30 kg K/t of grain produced [34].

Total milling rice yield

The TMY is one of the major parameters that determine the quality of rice, especially in a marketing perspective. Two types of milling yield such as HRY and TMY are considered the most important parameters of determining the quality of rice. A variety should possess a high turnout of HRY and total milled rice. Broken rice is generally valued at only 30–50% of the whole grain. The accurate measurement of the amounts and classes of broken grains is important and, hence, the standardized procedures are used for official grading. In the present study, the milling yield was low at early harvests (25 DAFF) as the immature grains did not have enough strength to tolerate the mechanical stresses applied during milling [37]. The results also revealed that the best time for harvesting to achieve a higher rice milling yield of direct seeded rice is between 30 and 35 DAFF similar to the previous study [12]. This pattern of variation was also observed in relation to HRY and true density (Figs. 1a and 2).

Head rice yield

From the consumer's perspective, the HRY is the most important physical quality parameter when determining the grain quality of rice. Harvesting paddy at the optimum crop maturity can give the maximum HRY [10, 38] but late harvesting causes significant reduction of the HRY [39]. Similar to the results of this study, another study had also reported that a higher HRY can be obtained when paddy was harvested between 30 and 35 DAFF [10]. Immature grains and low density of rice (Fig. 1a) may be the probable reason for lower HRY recorded during early stages of harvesting at 25 DAFF. This may also lead to higher grain breakage during milling. Delayed harvesting beyond 35 DAFF would also sharply reduce the true density (Fig. 1a) and, therefore, decrease the grain hardness resulting in higher breakages during milling (> 50%). Although the timeliness of harvesting significantly influences the milling yield, harvesting rice at the optimum crop maturity would result in the maximum HRY [38]. Any delay in harvesting causes reduction of the HRY [39] and extended delay in harvesting could lead to significant losses in HRY.

Wang et al. [9] reported that increased application of K fertilizer for paddy can significantly improve the percentages of brown rice, milled rice and HRY while reducing the grain chalkiness and enhancing grain protein content. Structural changes such as ordered arrangement of starch granules inside the seed endosperm are also possible with the increasing K fertilizers [23]. Potassium fertilizer is required for maximum yield and it must be applied during the vegetative growth stage [6]. This was clearly reflected by the results of HRY and TMY in the present study, which was significantly reduced with increasing age of harvesting (DAFF) and high rate of K fertilizer (MOP) application at the time of heading. Application of high doses of K fertilizer could also increase the percentage of rice bran [40]. The results revealed that application of 50% higher rate of MOP fertilizer at the time of heading (37.5 kg MOP/ha; approx. 18.75 kg K/ha) to a low shattering rice variety such as CIC 300 and harvesting paddy 5 days later than the recommended harvesting stage identified by Jayawardena [12] would increase the rice yield (APY, HRY and TMY) and grain quality under direct seeded rice in the dry zone of Sri Lanka.

Conclusion

The results of the present study showed that K fertilizer applied at the rate of 37.5 kg MOP/ha at the time of heading, which is 50% higher than the recommended rate, is the best among K fertilizer treatments to obtain the highest HRY when rice was harvested from 25 to 35 DAFF. The rice variety CIC 300 belongs to the 3 months age class (mature in 90–93 days after sowing) and, thus, the harvesting paddy between 35 and 40 DAFF could be considered as delayed harvesting. Harvesting before 30 or later than 35 DAFF, under different K fertilizer rates applied at the time of heading of the rice plant, would result in heavy losses during milling.

Abbreviations

LD: Low Country Dry Zone; TSP: triple super phosphate; MOP: muriate of potash; WAP: weeks after planting; DAFF: days after 50% flowering; K fertilizer: potassium fertilizer; APY: average paddy yield; TD: true density; BD: bulk density; GT: gelatinization temperature; L: grain length; B: breadth; L/B: length to breadth ratio; TMY: total milled rice yield; HRY: head rice yield; CP: crude protein; CF: crude fat; AC: apparent amylose; ANOVA: analysis of variance; DMRT: Duncan's multiple range test; df: degrees of freedom; SE: standard error.

Authors' contributions

All authors have equally contributed to the conceptualization and designing of the experiments and preparing the manuscript. AJA carried out the field studies, statistical analysis and interpretation. All authors read and approved the final manuscript.

Author details

[1] Agromony Division, Coconut Research Institute, Bandirippuwa Estate, Lunuwila 61150, Sri Lanka. [2] Present Address: Key Laboratory of Tropical Forest Ecology, Xiahuangbanna Tropical Botanical Garden, Chinese Academy of Sciences, Mengla 666303, Yunnan, China. [3] Present Address: University of Chinese Academy of Science, Beijing 100094, China. [4] Department of Food Science &

Technology, Faculty of Agriculture, University of Peradeniya, Peradeniya 20400, Sri Lanka. [5] Department of Agriculture Engineering, Faculty of Agriculture, University of Peradeniya, Peradeniya 20400, Sri Lanka. [6] Department of Crop Science, Faculty of Agriculture, University of Peradeniya, Peradeniya 20400, Sri Lanka.

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