RESEARCH

Effect of fertilizer management on potassium dynamics and yield of rainfed lowland rice in Indonesia

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ABSTRACT

Rainfed paddy fields have a significant role as a buffer for rice (*Oryza sativa* L.) availability in addition to irrigated paddy fields. However, the optimization of rainfed rice fields is constrained by low rice productivity caused by low soil fertility including K deficiency, especially in light textured soils. The objective of this study was to determine the effect of fertilizer management in light-textured rainfed rice fields on the K dynamic and lowland rice yields. The study was arranged with a randomized block design, six replicates, and five fertilizer treatments (control, NP, NPK, NP+composted straw, NPK+composted straw). The observed variables were grain yield, yield component, exchangeable K, and nonexchangeable K. The yield of rainfed rice plants significantly increased with fertilizer management. The direct seeded rice (DSR) yielded grains 1.23-1.65 t ha^{-1} higher than the transplanted rice (TPR). Plant K uptake significantly increased with fertilizer application, where NPK fertilizer increased K uptake by 88.6% (DSR) and 71.9% (TPR). Exchangeable and nonexchangeable K in soil were generally high at 40 and 60 d after germination, and decreased in harvest time. The nonexchangeable K was generally higher than exchangeable K at 20, 40, 60, and 100 d after germination. The application of straw compost not only significantly increased grain yield, but also effectively provided K for plants in the form of exchangeable K and K slowly available K, so it was effectively used as an alternative supply of K to replace K from inorganic fertilizers.

Key words: Direct seeded rice, fertilizers management, *Oryza sativa*, potassium dynamic, rainfed lowland rice, transplanted rice.

INTRODUCTION

Global food needs are always increasing along with the rate of population growth. To ensure the stability of food security, food production can be met by expanding the planted area through agricultural extensification and increasing productivity from agricultural intensification. Extensification is constrained by the availability of relatively fertile land and competition for its use between commodities, while intensification is constrained by low soil fertility and the availability of other supporting resources. The decrease in the area of irrigated rice (*Oryza sativa* L.) fields as the main supplier of food needs has forced rainfed rice fields to become an alternative buffer for food availability.

Rainfed rice fields are one of the mainstays agro-ecosystems to maintain food availability. Indonesia has rainfed rice fields with an area of 3 418 236 ha (ICADIS, 2020). The increasing rice production in rainfed rice fields is constrained by several factors, including erratic rainfall and low soil fertility, which causes low crop productivity. Even in light textured rainfed lowland soils, K is also a limiting factor. Rainfed lowland rice does not receive K in irrigation water, which is an important reason rice deficient K and additional K may be lost through leaching (Wihardjaka et al., 1999). Thus, yields in rainfed lowland average only 2.3 t ha^{-1} (Wade et al., 1999). Low soil fertility is also complex, because a large number of nutrients may be in limited supply, or toxic conditions may be present where soils are acid or saline (Wade et al., 1999; Schjoerring et al., 2019). Low yield of rainfed lowland in Central Java, Indonesia, is exacerbated by pest infestation in addition to drought stress and N and K deficiencies (Boling et al., 2004).

The need for K fertilizer in the last decade has increased sharply along with the increase in food demand (Hartati et al., 2018). Potassium is one of the essential macro nutrients needed for plant growth and development in relatively large quantities, as well as N and P nutrients. Potassium has a multifunctional role in agricultural production systems, namely in increasing resistance to pests and diseases, photosynthetic process, osmotic regulation, enzyme activity, stimulating and transport of assimilates, protein synthesis, ion homoeostasis, stability between monovalent and divalent cations in the transport of water through stomatal movement, helps plant turgor, stress tolerance, and enzyme stimulation (Hartati et al., 2018; Dhillon et al., 2019; Popp et al., 2020). Rice crop requires large quantities of K, and a continuous supply of K is necessary for heading growth stage after completion of the reproduction stage (Atapattu et al., 2018). Requirement of 200-300 kg K_2O ha^{-1} is necessary to obtain 5-10 t ha^{-1} of cereal crop yield (Atapattu et al., 2018). Potassium deficiency causes rice plants to be susceptible to diseases caused by *Helminthosporium oryzae*, *Rhizoctonia oryzae-sativae*, and blast (*Pyricularia oryzae*) (Williams and Smith, 2001; Wihardjaka and Abdurachman, 2007).

The availability of K varies with the soil's physical, chemical, and biological properties, parent material properties, weathering rate, addition of organic and inorganic fertilizers, leaching, erosion, and plants translocation (Dhillon et al., 2019). Potassium in the soil consists of soil solution K, exchangeable K, non-exchangeable K and mineral K (Habib et al., 2014). The main source of available K is K in the soil solution, which is in the range of 0.1%-0.2% of the total soil K (Dhillon et al., 2019). The availability of K in the soil depends on the release of K and weathering of the minerals mica, biotite, muscovite and illite (Ranjha et al., 2001). Clay types of 2:1 such as illite, vermiculite, mica often increase K fixation, so that K is not available to rice plants (Liao et al., 2013). The exchangeable K content ranges from 1%-2% of the total soil K (Dhillon et al., 2019; Sattar et al., 2019). Non-exchangeable K is an important contribution to plant K supply (Habib et al., 2014), where its content is 1%-2% of the total K soil (Dhillon et al., 2019). Most of the K in the soil is not available to plants, which is in the range of 96%-99% (Dhillon et al., 2019; Sattar et al., 2019). The low availability of K in the soil is caused by the transport of plant biomass at harvest, intensive cropping pattern, use of modern rice varieties for high yield, and the lessening or absence of K application (Ranjha et al., 2001; Sarkar et al., 2017). Rice crop removes about 100 kg K for a yield level of 5 t ha^{-1} (Saha et al., 2009); K deficiency is common in light textured soils, saline soils, and flooded soils (Dhillon et al., 2019).

The relatively expensive raw material for inorganic K fertilizer encourages the promotion of the use of organic matter to maintain soil fertility and crop production. However, organic matter does not always guarantee sustainable agricultural production (Sarkar et al., 2017). The balanced use of organic matter and inorganic fertilizers is the best practice approach to maintain soil health and crop productivity (Sarkar et al., 2017). Rice straw biomass is abundant at harvest, and its return to the soil is a source of K (Li et al., 2020). Returning composted straw to the soil can also reduce the impact of climate change (Kral et al., 2019). The behavior of K from inorganic fertilizers and organic matter also depends on soil moisture conditions (Wihardjaka, 2015).

Compared to irrigated paddy fields, rainfed paddy fields are more critical in nutrient management and water availability. In rainfed lowland ecosystem soil moisture regime greatly fluctuates during the growing period of the plants. Consequently, the nutrient availability status may also vary with time. Alternating dry-wet conditions affect the transformation of nutrients in the soil, especially K, so proper nutrient management is needed to increase the efficiency of nutrient use by plants. The fluctuation in soil conditions from anaerobic to aerobic also has enormous consequences for nutrient availability (Wade et al., 1999). Increasing the productivity of rainfed lowland rice through balanced fertilization management will certainly affect the availability of K in the soil, especially on light-textured soils. The objective of this research was to determine the effect of fertilizer management on the K dynamic and yield of rainfed lowland rice on light textured soils.

MATERIALS AND METHODS

Site description

The field experiment was carried out in rainfed rice (*Oryza sativa* L.) fields in Pati Regency (6°48'4" S, 111°10'23" E), Central Java Province, Indonesia, in the 2019/2020 wet season and 2020 dry season. Farmers generally adopt the typical rainfed cropping pattern of a dry seeded rice crop in wet season followed by transplanted rice crop in dry season, followed by secondary crops or fallow depending on rainfall water availability. The landscape is undulating and the soil is classified as Vertic Endoaquepts. The topsoil (0-20 cm-depth) properties of the site are a light texture with 48% silt and 11% clay (textural class is SiL), pH 5.3, 0.30% organic C, 0.04% total N, 13 mg kg^{-1} P extracted by Bray 1, cation exchange capacity of 5.5 cmol kg^{-1}, and exchangeable cations of K, Na, Ca, Mg as much as 0.04, 0.11, 3.97, 0.30 cmol kg^{-1}, respectively. The subsoil properties are pH 6.2, 0.12% organic C, 0.02% total N, 1.70 mg kg^{-1} P extracted by Bray 1, cation exchange capacity of 10.65 cmol kg^{-1}, and exchangeable cations of K, Na, Ca, Mg as much as 0.08, 0.40, 9.97, 1.17 cmol kg^{-1}, respectively. Based on meteorological data (2009-2016), average annual rainfall is 1465 mm, mean daily solar radiation ranges 389-559 MJ m^{-2} mo^{-1}, and average maximum and minimum temperatures are 34.8 and 23.2 °C, respectively (Table 1).

Experimental design and treatments

The experimental design used was a randomized block design, with six replicates and five fertilizer management treatments including control (T0), NP (T1), NPK (T2), NP+composted straw (T3), and NPK+composted straw (T4). The doses of NPK fertilizers were 120 kg N ha^{-1}, 36 kg P_2O_5 ha^{-1}, 60 kg K_2O ha^{-1}, respectively, while the dose of composted straw was 5 t ha^{-1}. The content in the composted straw used was 19.90% C, 0.52% N, 1.22% P, and 1.40% K. Based on the regulation of the Indonesian Ministry of Agriculture nr 261/2019, technical requirements for organic fertilizers must contain 15% more organic C, 8%-20% moisture content, and more than 2% of $N+P_2O_5+K_2O$.

Cultural practices

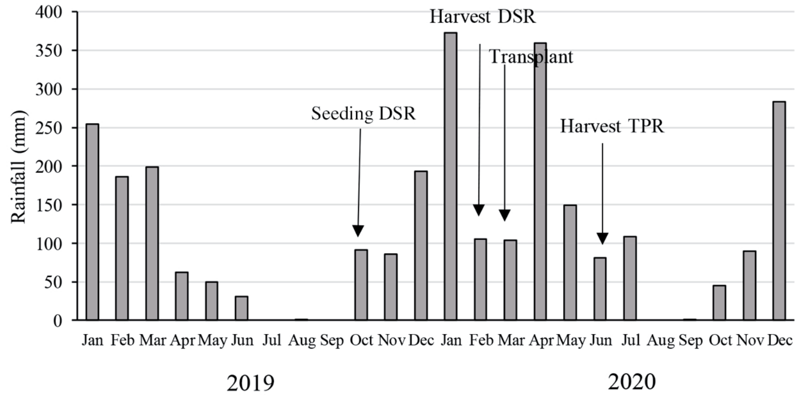
The soil tillage was done by plowing twice and levelling. Plotting was done to make plots with size of 5 m × 10 m. Composted straw according to the treatment was incorporated into the soils together with tillage. The land was left for 2 wk before planting time. The 'IR64' rice was planted using a direct seeded system in the 2019/2020 wet season and transplanting in the 2020 dry season. In the direct seeded rice (DSR) system, two seeds per hole were seeded using dibble with a spacing of 20 cm × 20 cm on 5 October 2019. The seeds started to germinate on 12 October 2019. In the transplanted rice (TPR) system, two rice seedlings were transplanted after 2 wk from the nursery on 1 March 2020 (Figure 1).

NPK fertilizers were applied according to list of the treatment. Nitrogen fertilizer was applied in three stages, namely 1/3N before planting, 1/3N at active tillering stage (35 d after germination), and the next 1/3N at panicle initiation stage (55 d after germination). Phosphorus fertilizer was applied at once before planting, whereas K fertilizer was applied in two stages, namely 1/2K before planting and the next 1/2K at panicle initiation stage (55 d after germination, DAG). Plant maintenance was carried out intensively, both weeding and controlling pests and plant diseases. Plants were harvested after the end of the ripening phase on 4 February 2020 for DSR and 3 June 2020 for TPR (Figure 1).

Table 1. Annual meteorological data of 2007-2016 period in experimental site.

			Average temperature	
Year	Annual rainfall	Average solar radiation	Minimum	Maximum
	mm	MJ m^{-2} mo^{-1}	°C	°C
2007	1256	427-557	22.8	31.3
2008	1476	367-559	21.6	32.0
2009	1163	379-577	23.7	31.8
2010	2330	404-507	24.2	28.5
2011	1409	400-551	23.2	32.0
2012	1153	355-566	21.5	35.3
2013	1699	388-613	23.8	37.7
2014	1534	330-569	23.6	38.3
2015	1170	470-559	23.0	39.6
2016	1846	374-536	24.1	40.4

Figure 1. Monthly rainfall distribution during growing rainfed lowland rice, 2019-2020.



DSR: Direct seeded rice, TPR: transplanted rice.

Parameters evaluated

Parameters evaluated included plant height, number of tillers, grain yield, yield components, K uptake, exchangeable K, and non-exchangeable K. Plant height and number of tillers were measured from 12 hills per plot. The grain yield was measured from area harvest of 2 m × 6 m and the moisture content in grains was measured. Yield components were observed from three hills per plot, including percentage of filled grain, total grain per panicle, and 1000-grain weight. Prior to harvest, samples of grain and straw for each plot were taken for analysis of total K which was used to calculate K uptake. Total K was determined by soaking with 1 N HCl and subsequent analysis of the filtrate using atomic absorption spectrophotometry (Boling et al., 2004). The nutrient uptake was calculated using formula from Sarkar et al. (2017) as follows:

$$\text{Nutrient uptake (kg K ha}^{-1}\text{)} = \text{Nutrient content (\% K)} \times \text{Grain yield (t ha}^{-1}\text{)}$$

Soil samples at depths of 0-15 and 16-30 cm were taken from each plot. From each plot, five subsample points were taken diagonally, and composited for analyzing exchangeable K (1 N NH_4OAc extraction method) and non-exchangeable K (1 M HNO_3 extraction method). Soil samples were taken when the plants were 20, 40, 60, and 100 DAG.

Data analysis

Data on grain yields, yield components and K uptake were analyzed ANOVA using SPSS v22 statistical program (IBM, Armonk, New York, USA). When the ANOVA showed significant differences among treatments, Tukey's test ($p < 0.05$) was used for pair-wise. Data of exchangeable K and nonexchangeable K were presented in the form of bars curve.

RESULTS AND DISCUSSION

Grain yield and plant K uptake

Lowland rice can be planted twice in rainfed rice fields by applying direct seeded rice system (DSR) in wet season followed by transplanted rice system (TPR) in dry season. The grain yield of DSR was 1.23-1.65 t ha^{-1} higher than that of TPR (Table 2). The yield potential of rainfed lowland rice is determined by the interaction between genotype, temperature, solar radiation, water regime, availability of essential nutrients, and the incidence of plant-disturbing organisms. The difference in grain yield between cropping seasons are mainly caused by the difference in weather (solar radiation, temperature, rainfall) beside nutrient deficiency especially K (Boling et al., 2007). Based on daily observations at the experimental site, the daily solar radiation during growing DSR and TPR ranged 14-18 and 14-16 MJ m^{-2} d^{-1}, respectively.

Grain yields of DSR and TPR increased significantly with fertilizer application ($p < 0.01$) (Table 2). The increase ranged from 66.9%-102.4% in DSR and 113%-172.6% in TPR. Application of K together with N and P did not significantly improve results compared to application of NP for both DSR and TPR. In contrast to the research of Kasno et al. (2020) that K nutrient fertilization in rainfed rice fields can increase rice yields of DSR between 0.20 and 1.38 t ha^{-1} or 3.6%-53.3%. The grain yield on NPK fertilization was not significantly different from either NP+composted straw or NPK+composted straw fertilization. Applying composted straw along with NP fertilizer even without K gives high grain yields. This means

Table 2. Grain yield and plant K uptake of rainfed lowland rice from some fertilizers management, Central Java province, Indonesia.

Treatments	Grain yield		K uptake	
	Direct seeded rice	Transplanted rice	Direct seeded rice	Transplanted rice
	t ha^{-1}		kg K ha^{-1}	
Control	2.51c	1.28c	47c	18c
NP	4.19b	2.73b	70c	64b
NPK	4.31ab	3.07bc	132b	110a
NP+composted straw	5.08a	3.43a	146b	114a
NPK+composted straw	4.81ab	3.49a	192a	132a

Numbers in same column followed same letters are not significantly different according to Tukey's test ($p < 0.05$).

application of composted straw could not only be attributed to provide available K, but also to enhance capacity of the soil to retain nutrients including soil K from being leached (Wihardjaka, 2016). Potassium is involved in the transportation of photosynthates from leaves to grain, thereby increasing the DM content of the plant and grain (Atapattu et al., 2018). The nutrient content in compost such as N and P also has a positive effect on the yield of rainfed rice. According to Liu et al. (2019), application of organic fertilizer promotes efficiency of inorganic fertilizer and enhances rice grain yield.

The composted straw used contained 1.4% K, meaning that the addition of 5 t ha^{-1} of composted straw contributed 70 kg K ha^{-1} to the soil. Crop residues, especially rice straw accumulate about 70%-80% of total absorbed K and its recycling would substantially save inorganic fertilizer and help soil K sustainability (Saha et al., 2009). Similar increase in grain yield due to straw application was also reported by some rice researchers (Saha et al., 2009). According to Li et al. (2020), crop straw return should be combined with K fertilization to not only offset soil K deficiency, but also improve K cycling. Nearly 80% of total K uptake came from the amount of K accumulated in the rice straw (Lu et al., 2017).

The high grain yield is also influenced by K uptake by plants. Grain yield at DSR was higher than TPR due to K uptake (Table 2) and yield component (Table 3) which was relatively higher in DSR. Potassium uptake in DSR was higher than in TPR. Nutrient uptake, especially K, is influenced by soil organic matter content, practical cultivation such as tillage, soil moisture conditions, drainage, drought stress, attack by plant-disturbing organisms, and availability of nutrients in the soil. The land began to be inundated during the active tiller growth phase until the DSR harvest, and the flooded land conditions continued during TPR growth, where water from rainfall supported this condition (Figure 1). The DSR with aerobic-anaerobic conditions generally cultivates the soil deeper than TPR (inundation condition) which allows penetration of plant roots to absorb greater nutrients (Hirzel et al., 2020). Potassium uptake in fertilizing without K was significantly lower than fertilizing with K either without or with compost (Table 2). The application of K together with N

Table 3. Growth and yield component of rainfed rice fields from some fertilizers management, Central Java province, Indonesia.

Treatments	Plant height	Tillers per hill: Maximum	Tillers per hill: Productive	Filled grain per panicle	Grains per panicle	Weight 1000 grains
	cm	nr	nr	%	nr	g
Direct seeded rice (DSR)						
Control	75.0c	17.6b	14.1b	73.1b	72.8c	27.18b
NP	83.2b	21.5a	15.2ab	78.1a	84.5b	28.32ab
NPK	87.9a	21.2a	16.3a	77.0ab	86.7ab	29.29a
NP+composted straw	89.9a	22.1a	16.6a	78.4a	91.5ab	28.73a
NPK+composted straw	90.6a	22.0a	15.6ab	76.3ab	94.7a	29.02a
Transplanted rice (TPR)						
Control	61.3c	6.5c	6.1c	75.8b	70.5b	24.81b
NP	73.5b	12.2a	10.6ab	76.1b	86.8a	26.00ab
NPK	78.3a	12.6a	10.8a	80.7a	94.2a	26.99a
NP+composted straw	77.4ab	11.0b	9.5b	80.8a	88.8a	27.62a
NPK+composted straw	79.9a	11.4ab	9.6b	79.0ab	92.3a	27.30a

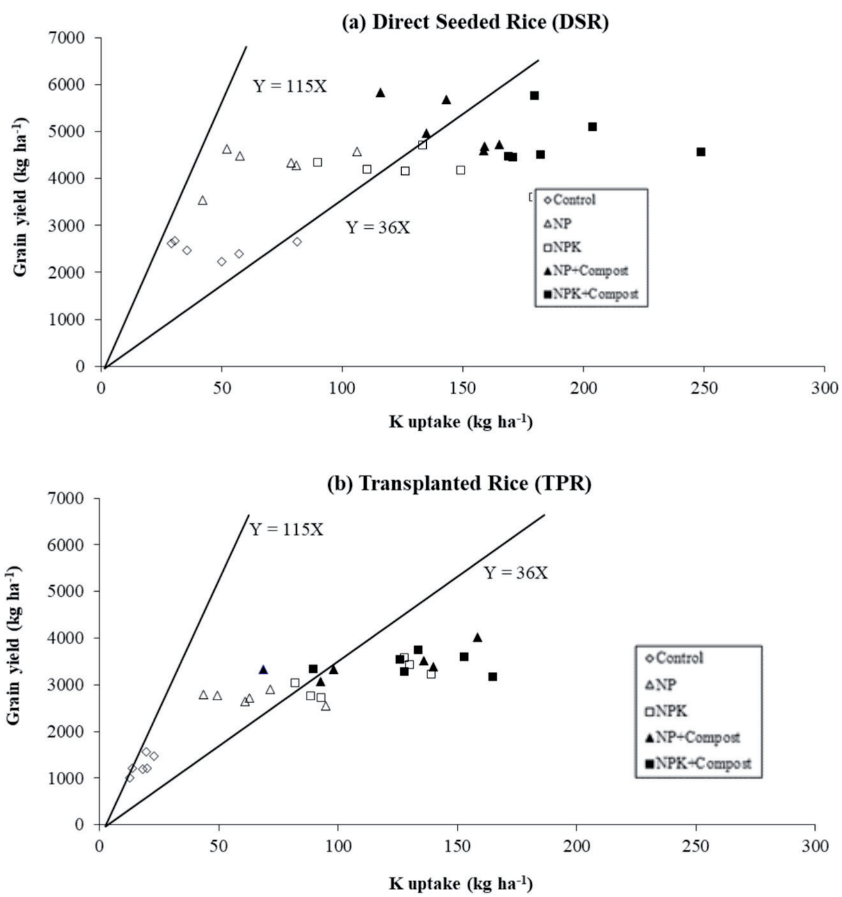
Numbers in same column followed same letters in each crop are not significantly different according to Tukey's test ($p < 0.05$).

and P fertilizers significantly increased K uptake by 88.6% (DSR) and 71.9% (TPR) (Table 2). According to Atapattu et al. (2018), K uptake requirement for rice that yield between 4 and 8 t ha^{-1} have ranged from 17 to 30 kg K t^{-1} grain produced (Atapattu et al., 2018).

The relationship between K uptake and grain yield on DSR and TPR is shown in Figure 2. According to Witt et al. (1999), maximum dilution K and maximum accumulation K are figured by lines Y = 115X and Y = 36X, respectively, where Y = grain yield and X = plant K uptake. The application of NPK, NP+composted straw, and NPK+composted straw resulted in excessive K accumulation, meaning that high K uptake was not accompanied by an increase in grain yield in both DSR and TPR. This indicated that K content in rice straw varied among treatments. Dobermann and Fairhurst (2002) showed that K contained in rice straw was much higher than in rice grain. Only in the control and NP treatments were located between the maximum dilution limit and the maximum accumulation limit, where K uptake was effective in providing grain yields (Figure 2).

The high uptake of K without an increase in grain yield also reflects the low recovery of K use efficiency calculated from GY divided by K uptake (Dhillon et al., 2019). The average recovery of K use efficiency in the control, NP, NPK, NP + compost, and NPK + compost treatments was 62, 51, 30, 32, 26 kg grain kg^{-1} K, respectively. Efficiency of K use decreased with increasing K level regardless of K sources (Saha et al., 2009). Recovery efficiency of K use in treatment of NPK is similar as reported by Witt and Dobermann (2004). With balanced fertilization (NPK), yield was increased primarily due to an increase in recovery and agronomic efficiency. Average recovery efficiencies of N, P, and K from mineral fertilizers in field trials with rice at 179 farmers' fields (n = 314) in five countries (China, India, Vietnam, Indonesia, and the Philippines) were 33%, 24%, and 38%, respectively (Witt and Dobermann, 2004).

Figure 2. Relationship between plant K uptake and yield of rainfed lowland rice direct seeded rice (DSR) (a) and transplanted rice (TPR) (b) in some fertilizers management.

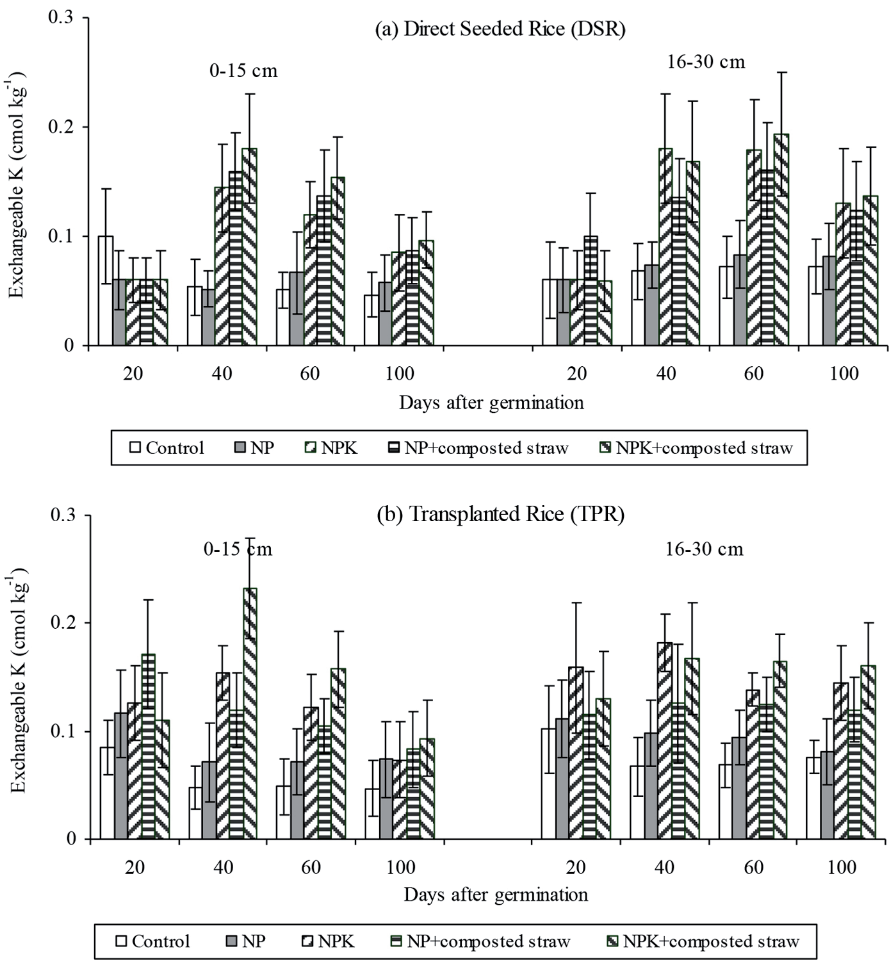


The increase in grain yield due to fertilizer application appears to be strongly related to the effect of yield components (Table 3). The yield component was significantly influenced by the application of fertilizer, both on DSR ($p < 0.01$) and TPR ($p < 0.01$). The yield component of DSR is relatively higher than that of TPR. The application of fertilizer containing K significantly increased height of rice plants, number of filled grains, and number of grains per panicle (Table 3). The number of rice panicle is the key factor for increasing grain yield (Wei et al., 2019). The supply of K can increase the number of grain contents and yields due to the improvement in the K status of plants which maintains plant physiological functions for the better such as plant photosynthesis (Schjoerring et al., 2019).

Potassium dynamics in soil

The need of available K for growth and development of rice plant varies at critical plant growth phases. Soil exchangeable K is normally considered readily available for plants, whereas non-exchangeable K is form of slowly available for plants (Lu et al., 2017). Figure 3 shows the dynamics of K in exchangeable form in several growth phases of DSR and TPR rainfed lowland rice. In the active tillering growth phase (20 DAG), the exchangeable K was less than 0.1 cmol kg^{-1} especially in DSR, and exchangeable tend increased at 40 and 60 DAG both at depths of 0-15 and 16-30 cm in the soil, and declined at 100 d after harvest in both rainfed lowland rice plants (Figure 3). The application of K fertilizer before seeding and at panicle initiation stage must affect K content in soil. It is expected that 0-15 cm layer of NPK, NP + compost and NPK + compost at 20 DAG seems higher exchangeable K than control and NP, then exchangeable K decreases at 40 and 60 DAG gradually by plant K uptake and leaching during active tillering stage. Supplemental K applied at panicle initiation stage may affect exchangeable K at 100 DAG.

Figure 3. Exchangeable K in different depth soil on some fertilizers management in direct seeded rice (DSR) (a) and transplanted rice (TPR) (b).



The exchangeable K in treatments of control and NP were generally less than 0.1 cmol kg^{-1} at depths of 0-15 and 16-30 cm in both DSR and TPR. Fertilization of NPK, NP+composted straw, and NPK+composted straw significantly increased exchangeable K especially at 40 and 60 DAG. Composted straw can be used to replace inorganic K fertilizer, whereas straw compost can increase exchangeable K in the soil. Compared to NP treatment in DSR, compost increased exchangeable at 20, 40, 60, 100 DAG by 0.03, 0.11, 0.07, 0.03 cmol kg^{-1} (0-15 cm depth), and 0.04, 0.07, 0.08, 0.04 cmol kg^{-1} (depth 16-30 cm), respectively. However, in TPR compost was effective in increasing exchangeable K only at 40 and 60 DAG as much as 0.039, 0.043 cmol kg^{-1} (0-15 cm depth), and 0.033, 0.044 cmol kg^{-1} (16-30 cm depth), respectively (Figure 3). At 100 DAG, exchangeable K in 0-15 cm depth was lower than 16-30 cm depth in both rice plants (Figure 3). This indicates that K undergoes leaching to a deeper layer. Loss of K from leaching through percolation in light textured soils depends on the amount of exchangeable K, that is, 5% of the exchangeable K (Wihardjaka et al., 1999), rice root distribution and K uptake by plant (Kirkman et al., 1994).

From Figure 3 is seen that exchangeable K at the beginning growth of TPR is more than 0.1 cmol kg^{-1} which is equivalent to 8.68 kg K ha^{-1} (0-15 cm depth, BV = 1.48 g cm^{-3}) and 9.44 kg K ha^{-1} (16-30 cm depth, BV = 1.61 g cm^{-3}). The exchangeable K at early growth of the TPR is possible from residual exchangeable K in the previous season (WS 2019/2020) and indigenous exchangeable K. The dynamics of exchangeable K at different soil depths in rainfed lowland affect the increase in grain yield and plant K uptake. The value of each depth depends on processes that tend to decrease exchangeable K, namely K absorption, immobilization in the form of nonexchangeable and leaching, while the increase in exchangeable K is prone from nonexchangeable and plant-mediated forms (Wihardjaka et al., 1999).

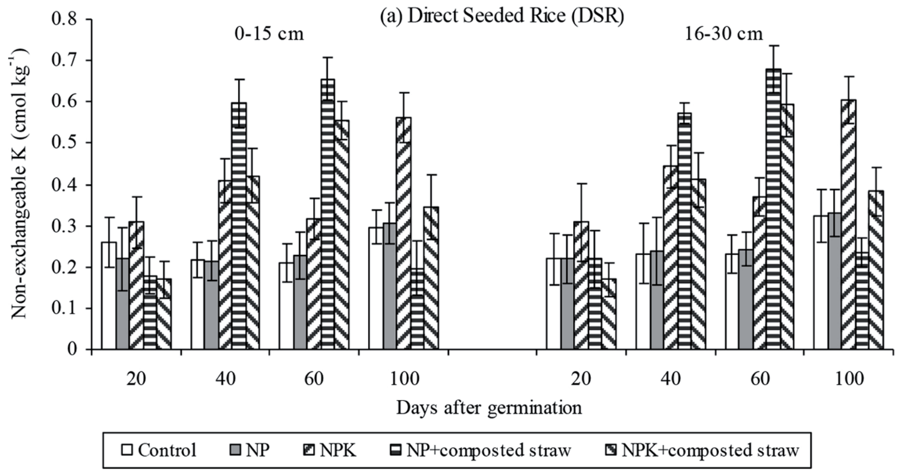
When the exchangeable K is relatively high, it will be fixed partly in the clay mineral lattice and leached to deeper layers. The K ions may undergo fixation or adsorption on the soil materials immediately following fertilization when K^+ levels in solution and exchangeable form are high (Liao et al., 2013). In Figure 4, it can be seen that the non-exchangeable K increases with the age of the rainfed lowland rice plants, both DSR and TPR. The non-exchangeable K in control and NP treatments was higher than the exchangeable K, which was more than 0.2 cmol kg^{-1} in 0-15 cm depth (equivalent to 17.36 kg K ha^{-1}) and in 16-30 cm depth (equivalent to 18.88 kg K ha^{-1}). The application of NPK, NP+composted straw, and NPK+composted straw significantly increased non-exchangeable K higher than control and NP in both soil depths. The highest non-exchangeable K was seen in the treatment of NP+composted straw when the plants were 60 DAG.

Straw compost can increase nonexchangeable K in the soil. In DSR, composted straw increased non-exchangeable K at 20, 40, 60, 100 DAG by 0.05, 0.05, 0.03, 0.01 cmol kg^{-1} (0-15 cm depth), and 0.01, 0.03, 0.03, 0.04 cmol kg^{-1} (16-30 cm depth), respectively. However, in TPR composted straw was effective in increasing non-exchangeable K only at 40 and 60 DAG as much as 0.32, 0.39 cmol kg^{-1} (0-15 cm depth), and 0.30, 0.39 cmol kg^{-1} (16-30 cm depth), respectively (Figure 4). The high non-exchangeable K in the soil has the potential as a K reserve when the K availability for plants decreases. When the K^+ concentration in the soil solution falls below a certain level, K fixed can be gradually released and become available for uptake by plants (Liao et al., 2013).

The release of K from the non-exchangeable form increases plant growth and K uptake. The accelerated solubility of K from K slowly-exchangeable in interlayer clay and K structure in clay and silt fractions to a form available to plants is due to the high rate of diffusion, H^+ ions produced by plant roots, and stimulated by the presence of some microbes in the rhizosphere. Potassium release occurs when H^+ export from roots balances excess intake of cations over anions under NH_4^+ nutrition and H^+ generation in Fe^{2+} oxidation by root-released O_2 (Wihardjaka et al., 1999). Several groups of rhizobacteria and fungi can be involved on solubilization of K minerals in the soil system, namely groups of rhizobacteria (*Acidithiobacillus ferrooxidans*, *Agrobacterium tumefaciens*, *Bacillus edaphicus*, *B. mucilaginosus*, *B. circulans*, *Burkholderia* sp., *B. megaterium*, *Paenibacillus* sp., *Pseudomonas* sp., *Rhizobium pusense*) and group of fungi (*Aspergillus niger*, *A. terreus*, *Glomas mosseae*, *G. intraradices*, and *Penicillium* sp.) (Sattar et al., 2019).

Information on K content in the soil, amount of input, and plant K uptake can be used to determine the K balance. The K balance in this paper is only calculated from the initial K exchangeable plus K input minus plant K uptake. It can be seen in Figure 5 that K uptake is generally higher than the initial K and K inputs in all treatments. All treatments showed a negative K balance, except for the treatment of NPK + compost in TPR. The K balances in control, NP, NPK, NP + compost, NPK + compost treatments were -36, -59, -71, -64, -61 kg K ha^{-1} (in DSR) and -7, -51, -41, -26, +9 kg K ha^{-1} (in TPR), respectively. The high K uptake of plants is thought to be supplied from the slowly available K (form of non-exchangeable K). The return of straw into the soil significantly affects the K balance (Lu et al., 2017).

Figure 4. Non-exchangeable K in different depth soil on some fertilizers management in direct seeded rice (DSR) (a) and transplanted rice (TPR) (b).



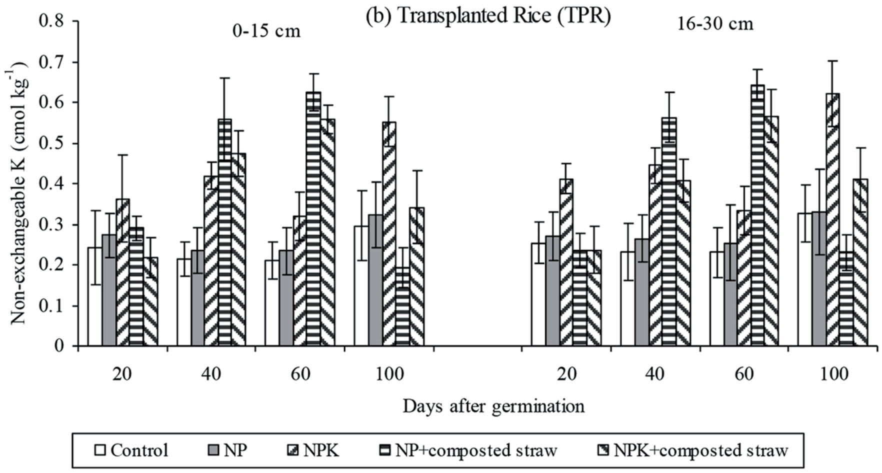
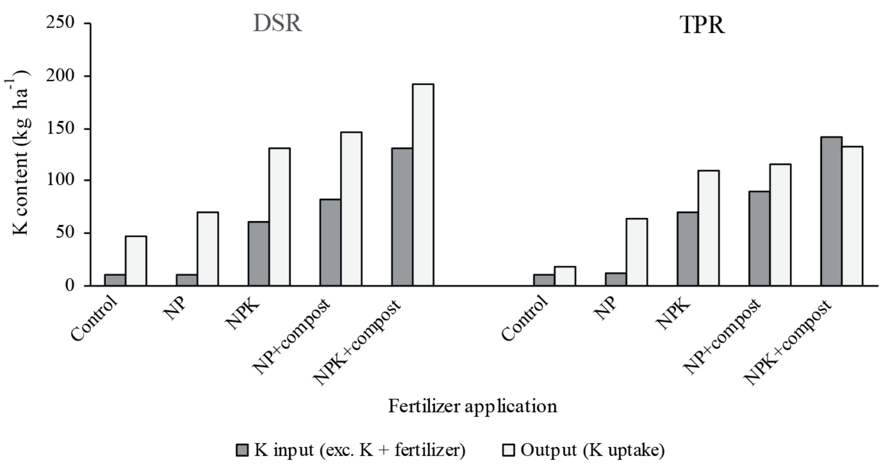


Figure 5. Potassium balance in rainfed lowland rice applied by some fertilizers management.



DSR: Direct seeded rice, TPR: transplanted rice.

CONCLUSIONS

Rainfed lowland rice plants responded to fertilization where the grain yield of rainfed rice was significantly affected by fertilization both in direct seeded rice (DSR) and transplanted rice (TPR). The increase in plant K uptake affects the high grain yield of rainfed rice, but also the fertilizers application, especially NPK, NP+composted straw, and NPK+composted straw tends to cause excessive K accumulation in rice plants. The high K uptake by rainfed rice plants tends to cause negative K balance. The application of NP+composted straw gave grain yields that were not significantly different than with the NPK application. Besides providing K for rice plants, composted straw also increases the capacity of the soil to fix K soil and avoid K loss due to leaching process.

The exchangeable and non-exchangeable K increased at some critical rice growth stages. The exchangeable and non-exchangeable K were relatively higher at 40 and 60 d after germination than at the beginning of growth and towards the end of the ripening stage. Non-exchangeable K is generally higher than exchangeable K, where non-exchangeable K has the potential to be absorbed by plants when exchangeable K is declined, even though it is slowly available to plants. The application of composted straw was effective in increasing exchangeable and non-exchangeable K in the soil at a depth of 0-15 and 16-30 cm.

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