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GROWTH AND YIELD-RELATED TRAITS OF KHAO DAWK MALI 105 (KDML105) RICE IN PADDY AND UPLAND CONDITIONS

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ABSTRACT

Drought is a major factor limiting the production and quality of rice. In recent years, damage caused by drought in rainfed lowland rice areas has become a serious problem in Thailand. The study sought to clarify Thai Jasmin rice's growth and yield-related traits compared with three other rice cultivars under paddy and upland conditions. The effects of different water supply levels, corresponding to paddy and upland conditions on four rice cultivars, i.e., KDML105, Dro1-IR64, Kinandang Patong (KP), and IR64 were examined. All four cultivars under upland conditions demonstrated decreased growth (plant height and number of tillers per plant), photosynthesis rate, transpiration rate, stomatal conductance, number of panicles per plant, percentage of filled grains, number of spikelets per panicle, 1000-grains weight and the number of spikelets per plant of rice, whereas the 50% days to heading (50% DTH) increased. The 50% DTH of KDML105 indicated that this cultivar's flowering time occurs later even under paddy conditions, and the longer days (218.5 days) under dehydration stress conditions. Compared to the paddy conditions, the 50% DTH under upland conditions increased by 10.91% for KDML105, 19.51% for Dro1-IR64, 18.91% for KP, and 17.81% for IR64. Regarding yield-related traits, the percentage of filled grains under upland conditions was reduced by 3.77% in KP, 3.97% in IR64, 9.10% in Dro1-IR64, and 12.42% in KDML105 compared with the paddy conditions. KDML105 rice is less resistant to drought compared to the other varieties, and KDML105 is not significantly affected by yield-related traits under water stress conditions. However, this cultivar's long growing season as a photosensitive variety exposes it to drought risk for a long period, and this will affect rice production in the long term. To avoid this unexpected feature, the improvement of non-sensitive varieties is a challenge that should be addressed in the near future against climate risks.

Key words: drought tolerance, photosynthetic trait, Thai Jasmine rice

INTRODUCTION

Rice (*Oryza sativa* L.) is one of the world's most important food crops (Liu et al. 2006). The world's population has doubled since the early 1960s, and the existing yields of the major cereal crops are projected to be insufficient to meet the food needs of the future (Somchai 2005). Among the many varieties of rice, Khao Dawk Mali 105 (KDML105) is the most important rice in Thailand's economy because of its ease of preparation and features (e.g., stickiness, softness, and pleasant fragrance); these characteristics made KDML105 rice popular with consumers. However, KDML105 can be planted only once a year during the rainy season because of cultivation constraints, including the seasonal change in day length. KDML105 is not a well-known drought-tolerant variety, but its adaptability in a rainfed lowland ecosystem was ascribed to the plasticity of the root system under abiotic stresses (O'Toole and Bland 1987).

The total rice-growing area of Thailand is 9.47 million ha, and the northeast region has the highest production of rice, accounting for 5.22 million ha (63.10%) of Thailand's rice-growing area, followed by the north, central, and south regions, which account for 22.49%, 14.38%, and 1.33% of the area where rice is planted, respectively (Office of Thai Agricultural Economics 2019). Thailand's rice crops are commonly grown under rainfed lowland conditions without irrigation water (Kamoshita et al. 2008). If water deficit problems or inadequate precipitation occurs during the rainy season, the changes in the rice's physiological and biochemical properties will inhibit plant growth (Fukai and Cooper 1995), thus affecting rice development and reducing rice production (Wang et al. 2019). Drought stress affects water metabolism in plants, preventing nutrient uptake, restricting the transpiration rate and plant growth, interfering with physiological and biochemical processes, and decreasing the yield and quality (Maghsoudi et al. 2016).

In Thailand, most of rice-growing areas in the rainfed regions have a relatively limited amount of water, which affects the plants' growth and decreases rice production (Hanson et al. 1990). Drought is a severe factor that limits rice production and quality. Lack of water can cause a reduction in the number of panicles and developed seeds (Liu et al. 2006). When rice plants are subjected to drought during the growing season, the yield is reduced by approx. 17% plus by another 30% during the reproductive stage, when the formation of the young grains takes place (Thawatchai 1992). This is consistent with earlier findings showing that higher temperatures cause water shortages that in turn increase the water evaporation in plants' anthers, resulting in abnormal male pollen (Mohammed and Tarpley 2011). A drought can thus severely limit the quantity and quality of rice.

The present study sought to evaluate growth characteristics and yield of the rice cultivar Khao Dawk Mali 105 (KDML105) and its ability to resist drought stress in comparison with three other rice cultivars under different water regimes, toward the goal of using information obtained to develop and improve rice varieties in the future.

MATERIALS AND METHODS

Plant materials and growth conditions. Thai rice cultivar KDML105 was evaluated alongside the shallow-rooting cultivar IR64, the deep-rooting cultivar Kinandang Patong (upland rice), and the cultivar Dro1-IR64, which is a near-isogenic line homozygous for the Kinandang Patong (KP) allele of Deeper Rooting 1 (DRO1) in the IR64 genetic background. Seeds of each cultivar were sown in nursery boxes to germinate in a greenhouse and transplanted after 30 days: one seedling per hill in a concrete tank under both paddy and upland conditions. The soil moisture content was controlled at 2.0–2.2 kPa at 20 cm from the soil surface using a pF-meter (TAKEMURA Electric Works Ltd., Tokyo, Japan) to achieve a water deficit in the upland condition. Fertilizer (N-P_2O_5-K_2O) was applied at 30 and 60 days after transplanting at 25:25:25 kg/ha and 25:0:0 kg ha^{-1}, respectively. The experiments were conducted from May 2019 to October 2019 at the Tokyo University of Agriculture, Tokyo, Japan.

Data measurement. The plant height and tiller number per plant as growth parameters were recorded. The photosynthetic rate, transpiration rate, and stomatal conductance were recorded by using the plant photosynthesis analyzer (LCi-SD, ADC BioScientific Ltd., UK) equipped with blue and red-light sources to measure photosynthesis under 1000 mmol m^{-2} s^{-1} photosynthetic photon flux density (PPFD) and a 500 mmol s^{-1} flow rate at 70 days post-transplantation (the booting stage). The photosynthetic parameters of the rice plants were analyzed between 9:00 and 11:00 a.m. at the middle part of the most developed leaf (Zhang et al. 2017). The following yield-related traits were recorded: 50% days to heading (50%DTH), the number of panicles per plant, the percentage of filled grains per panicle, the number of spikelets per panicle, the 1000-grains weight, and the number of spikelets per plant.

Statistical analysis. Statistical differences were determined using SPSS Statistics ver. 22 (Chicago, IL, USA). Mean differences were compared by Duncan's multiple range test (DMRT) and t-test at a probability level of 0.05. A principal component analysis (PCA) of the mean-centered average results from the four rice cultivars and the two conditions (paddy and upland) was conducted. The PCA axes 1 and 2 were tested with the SPSS software.

RESULTS AND DISCUSSION

Plant growth. The growth parameters of the rice cultivars under paddy and upland conditions are summarized in Table 1. Under upland conditions, all traits were influenced by the agronomic characteristics of KDML105 and the other three rice cultivars. Compared to paddy conditions, the upland condition decreased significantly plant height in all cultivars by 7.01% in KDML105, 17.70% in Dro1-IR64, 15.32% in KP, and 17.95% in IR64. These data demonstrated that KDML105 had the least decrease compared to other rice cultivars, and this decrease was due to the specific characteristics of the KDML105 cultivar, which has a plant height at 140–150 cm (ORDPB 2012). At the same time, the tiller number per plant differed significantly between the cultivars KP and IR64. This is consistent with the study reported by Manal et al. (2014) showing that rice grown under a decreased water supply exhibit reduced plant height, leaf area, root length, and root biomass (Rodriguez et al. 2005; Kang and Futakuchi 2019). In addition, drought hinders leaf and tiller development at the vegetative stage of rice (Pantuwan et al. 2002). Sunflowers grown under dehydration, showed decreased plant height, root length, total leaf area, and total dry weight compared to sunflowers grown under normal conditions (Manivanna et al. 2007)

Relative chlorophyll content (SPAD). The comparison of the water resistance of the four rice varieties revealed that the environmental conditions and rice cultivars significantly affected the soil and plant analyzer development (SPAD) value, which is a measure of the relative chlorophyll concentration of leaves (Netto et al. 2005). The rice variety with the highest SPAD value was KP (44.48), followed by KDML105 (40.40 units) and Dro1-IR64 and IR64, the values of which were not significantly different, 39.22 and 39.24 units, respectively (Table 1). Compared to the paddy condition, the upland condition significantly increased the cultivars' SPAD values; the SPAD value of IR64 increased by 26.17%, that of KP by 25.98%, KDML105 by 25.90%, and Dro1-IR64 by 20.40% (Table 1). Darunee et al. (2017) reported that dehydration affects the increase in SPAD because chlorophyll density was increased under drought conditions (Arunyanark et al.2008; Zokaee-Khosroshahi et al. 2014) causing higher chlorophyll content per unit leaf area (Songsri et al. 2009). The present findings reveal a significant increase in SPAD values in rice grown in water-shortage conditions, which has also been reported for potato (Rolando et al. 2015) and snap beans (Nemeskéri et al. 2017). This phenomenon may be due to the alterations of the water and chlorophyll content in the leaves, accompanied by decreased photosynthetic active light absorbance; the large reflectance is thus manifested in high SPAD values (Rolando et al. 2015).

Photosynthetic rate, transpiration rate, and stomatal conductance. The comparison of the four rice cultivars under different irrigation conditions demonstrated that the rate of photosynthesis (Pn), transpiration rate (T), and stomatal conductance (Sc) were all significantly affected ($p \leq 0.01$). Compared to the paddy condition, the photosynthetic rate was lower for all cultivars grown under the upland condition. The photosynthetic rates under the upland condition were significantly decreased in Dro1-IR64 and IR64 by 41.48% and 39.07%, compared to the paddy condition while those of KDML105 and KP were relatively smaller at 19.37% and 20.09%, respectively (Table 1).

Table 1. Effects of water deficit on the growth, photosynthetic rate, transpiration rate, and stomatal conductance of the four rice cultivars.

Cultivar	Condition	Plant height (cm)	Tiller number/ plant	SPAD	Photosynthetic rate (μmol m^{-2} s^{-1})	Transpiration rate (mmol m^{-2} s^{-1})	Stomatal conductance (mmol m^{-2} s^{-1})
KDML105	Paddy	123.34 **	12.17 ns	35.45 **	5.99 ns	3.07 **	0.073 ns
	Upland	114.69 (−7.01)	10.42 (−14.38)	44.63 (+20.57)	4.83 (−19.37)	1.16 (−62.21)	0.050 (−31.51)
Dro1-IR64	Paddy	103.30 **	15.19 ns	35.59 **	7.69 **	5.85 *	0.344 **
	Upland	85.02 (−17.70)	15.10 (−0.59)	42.85 (+16.94)	4.50 (−41.48)	2.27 (−61.20)	0.082 (−76.16)
KP	Paddy	141.35 **	4.72 **	39.73 **	7.29 ns	4.94 **	0.191*
	Upland	119.70 (−15.32)	2.74 (−41.95)	50.03 (+25.92)	5.76 (−20.99)	2.07 (−58.10)	0.065 (−65.97)
IR64	Paddy	97.91 **	14.93 *	34.70 **	7.96 **	4.41 *	0.143 *
	Upland	80.34 (−17.95)	11.67 (−21.84)	43.78 (+20.74)	4.85 (−39.07)	2.51 (−43.08)	0.090 (−37.06)
Cultivar		**	**	**	ns	**	**
Condition		**	**	**	**	**	**
Cultivar × Condition		**	*	*	ns	*	*

Values in the parentheses indicate an increase (+) and decrease (-) in each parameter under upland conditions.
*p<0.05, **p<0.01, ns: not significantly different by t-test.

Drought affects various steps of the photosynthetic pathway by impairing pigments, photosynthesis, gas exchange, and photosynthetic enzymes in the plants (Asharf and Harris 2013). A similar trend was observed in this study but the degree of reduction was smaller for KP and KDML105 suggesting that KP grown in upland cultivation and KDML105 grown in rain-fed lowland cultivation are adapted to dry conditions. The transpiration rate (T) and stomatal conductance (Sc) in the upland-grown cultivars were significantly reduced compared to those grown in the paddy condition. Reductions in Sc of the shallow-rooted KDML105 and IR64 were smaller than those of the deep-rooted Dro1-IR64 and KP. Stomatal conductance is a major factor in plant photosynthesis (Reddy et al. 2004; Farooq et al. 2009), because a decrease in Sc decreases carbon dioxide (CO_2) fixation.

Generally, chloroplasts are an essential part of the photosynthesis process damaged by reactive oxygen species (Smirnoff 1995). When stomata conductance decreases, the level of photosynthesis also decreases. Drought-tolerant rice cultivars also exhibit intense stomatal closure by reducing stomatal conductance more effectively compared to drought-susceptible cultivars (Ji et al. 2012).

Heading and yield-related traits in a water-deficit condition. Table 2 provides the 50% days to heading (50% DTH) data of the four rice cultivars under paddy and upland conditions. Both the cultivar and the treatment (paddy vs. upland) significantly affected the number of days to heading ($p \leq 0.01$). The water deficit was associated with a substantial delay in the heading date (Table 2). The heading was delayed by 21.5–24.0 days in the upland condition compared to the paddy condition (KP had the lowest 50%DTH, followed by Dro1, IR64, and KDML105, respectively). The heading date or rice grown in a short-day (SD) condition was earlier than that in the long-day (LD) condition, and the heading date of a mutant was earlier than that of the wildtype (Saikumar et al. 2016; Luan et al. 2009). It was observed that KDML105 was the wildtype and very sensitive to environmental factors, especially the photoperiod and temperature. For this reason, it takes more time to flower.

The heading was delayed by water-deficit stress. Although KDML105 showed a longer growing season due to the changing day length in this study conducted in Japan, the delay in heading due to the water-deficit condition was relatively small compared to the other three cultivars. KDML105 is a strong photosensitive variety, and this characteristic suppresses heading under LD conditions and promotes it under SD conditions (Izawa 2007). Rice heading is well known to be delayed under low-temperature conditions (Luan et al. 2009). The most important quantitative trait loci (QTLs) for the flowering process in rice are Hd1 and Hd3a (Kojima et al. 2002); Hd1 promotes the expression of Hd3a under SD conditions and inhibits it under LD conditions (Yano et al. 2000; Izawa et al. 2002; Zhang et al. 2012; Nemoto et al. 2016). Even within a genotype, drought stress strongly affects heading delays (Kang and Futakuchi 2019).

Table 2 provides the data of the yield-related traits, i.e., the number of panicles per plant, the % of filled grains per panicle, the number of spikelets per panicle, the 1000-grains weight, and the number of spikelets per plant. Under the upland condition, all of these traits except the number of spikelets per panicle of KP were lower than the corresponding values under the paddy condition (Table 2). The number of panicles per plant was decreased in all cultivars under the upland condition, with KP showing the greatest reduction (−51.50%), followed by IR64, KDML, and Dro1-IR64 (−27.82%, −19.47%, and −5.70%, respectively). Compared to the paddy field condition, the percentage of filled grains per panicle decreased under the upland condition. The most significant decrease was observed in KDML105 (12.42%), followed by Dro1-IR64, KP, and IR64, (9.10%, 3.97%, and 3.77%, respectively) (Table 2).

Table 2. Effect of water deficit on days to 50% days to heading (50%DTH) and yield components of the four rice cultivars

Cultivar	Treatment	50% DTH, days	No. of panicles per plant	% Filled grains per panicle, %	No. of spikelets per panicle	1000-grains weight, g	No. of spikelets per plant
KDML105	Paddy	197.00 **	6.42 *	56.50 **	87.35 **	25.60 ns	563.79 **
	Upland	218.50 (+10.91)	5.17 (−19.47)	49.48 (−12.42)	65.75 (−24.73)	24.12 (−5.78)	339.49 (−39.78)
Dro1-IR64	Paddy	123.00 **	11.58 **	85.71 ns	154.21 *	27.05 *	1789.78 *
	Upland	147.00 (+19.51)	10.92 (−5.70)	77.91 (−9.10)	142.71 (−7.46)	25.25 (−6.64)	1556.45 (−13.04)
KP	Paddy	119.00 **	4.33 **	83.68 ns	280.39 ns	23.22 ns	1212.28 **
	Upland	141.50 (+18.91)	2.10 (−51.50)	80.52 (−3.77)	281.70 (+0.47)	21.07 (−9.26)	591.55 (−51.20)
IR64	Paddy	123.50 **	12.58 *	80.27 ns	149.90 **	25.53 ns	1885.22 **
	Upland	145.50 (+17.81)	9.08 (−27.82)	77.08 (−3.97)	133.92 (−10.66)	23.77 (−6.89)	1215.31 (−35.53)
Cultivar		**	**	**	**	**	**
Condition		**	*	**	**	**	**
Cultivar × Condition		**	**	ns	ns	ns	*

Values in the parentheses indicate an increase (+) and decrease (-) in each parameter under upland conditions.
*p<0.05, **p<0.01, ns: not significantly different by t-test

The low temperature during the ripening period may have affected the percentage of filled grains per panicle of KDML105 since the heading date in Japan was late (October). In addition, it was observed that drought affects rice yields (Mohammed and Tarpley 2011). Higher temperature is one of the reasons for dehydration, which influences the ability of the pollen to cause abnormalities (Mohammed and Tarpley 2011; Rang et al. 2011) another study indicated that the amount of pollen that can be pollinated was reduced under higher temperatures (Rang et al. 2011). In addition, drought stress at the vegetative stage caused a 50% reduction in the grain yield because the drought hindered the leaf and tiller development, subsequently affecting the development of panicles and thus causing an approx. 17% yield loss (Swain et al. 2017; Thawatchai 1992; Pantuwan et al. 2002); a 30% reduction at the reproductive stage with the formation of the young grains due to a decrease in the number of filled grains per panicle was also described (Thawatchai 1992; Pantuwan et al. 2002). When stress was applied between panicle initiation and pollen meiosis, the decreased yield was also affected by the flowering delay and a delay in panicle excretion (Saikumar et al. 2016) due to the delay in floral development (Lafitte et al. 2004).

The relationship between environmental conditions and rice cultivars. To evaluate the effects of the rice cultivar under water deficit conditions, a PCA was conducted using a correlation matrix of seven traits: 50% DTH, SPAD value, photosynthetic rate, transpiration rate, stomatal conductance, number of panicles per plant, and number of spikelets per panicle. The contribution of the first principal component was 57.27% for all variations, with high positive correlations with the transpiration rate, photosynthetic rate, and stomatal conductance, and a high negative correlation with 50% days to heading and SPAD value, indicating that these factors are related to photosynthesis and earliness. The second principal component, with a contribution rate of 27.01%, SPAD value was highly positively correlated with the number of panicles per plant and strongly negatively correlated with the number of spikelets per panicle, and the SPAD value can thus be considered a factor related to yield-related traits in terms of the number of panicles per plant and the number of spikelets per panicle (Fig. 1).

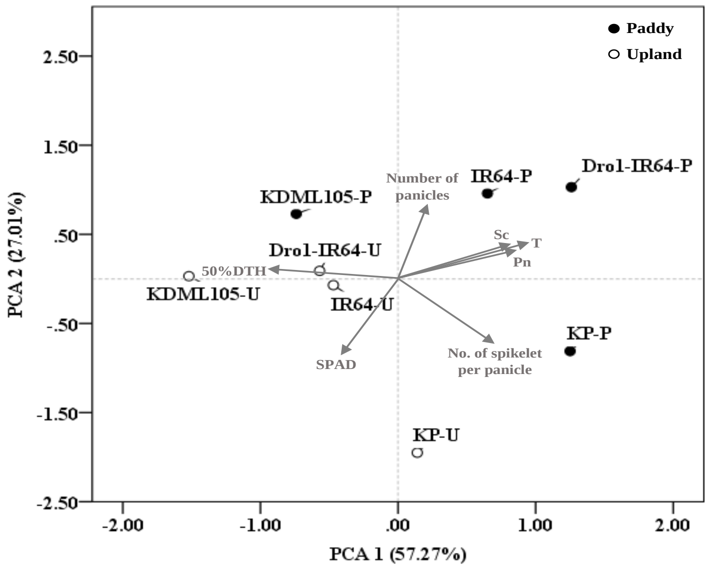

Fig. 1. The principal component analysis (PCA) biplot for the ordination of growth and yield from the rice cultivars KDML105, Dro1-IR64, KP, and IR64 under two paddy and upland conditions. Ps: photosynthesis rate, Sc: stomatal conductance, T: transpiration rate.

Scatter plots for the scores of the first and second principal components demonstrated that under the upland condition, all four rice cultivars showed reduced photosynthetic traits of transpiration rate, photosynthetic rate, and stomatal conductance, longer 50% DTH periods, and reduced numbers of panicles per plant and numbers of spikelets per panicle. Compared to the other cultivars, KDML105 showed lower photosynthesis-related factors under both paddy and upland conditions. Water stress reduced the standard pace of Pn, Sn, and T (Farooq et al. 2009) while the days to heading increased (Luan et al. 2009).

The correlation coefficient between PCA1 and the number of spikelets per plant was r=0.981, a significant correlation (Fig. 2). These results indicate that water deficit factors and yield have relatively little effect on KDML105 compared to the other tested cultivars, even under a water-deficit condition. The KDML105 has adapted to rainfed cultivation and irregular droughts and water deficits. On the other hand, KDML105 is a strong photosensitive variety and inhibits flowering under LD conditions (Izawa 2007). Late flowering and exposure to low temperatures during the ripening period of KDML105 affected the percentage of spikelets (Fig. 2).

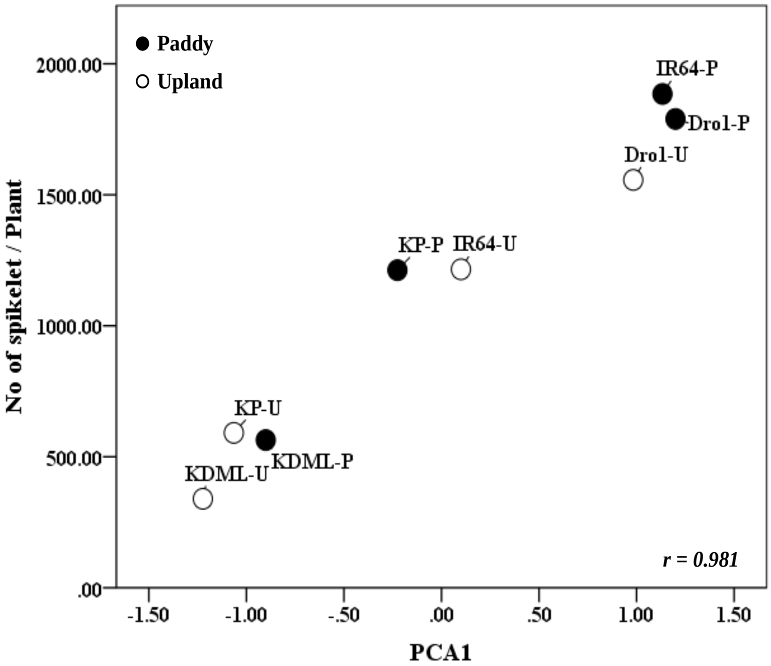

Fig. 2. The ability to adapt to dehydration conditions of all four rice cultivars by using the relationship between principal component 1 (PCA1) and the number of spikelets per plant under paddy and upland conditions.

CONCLUSION

The result of this study can be concluded that the water deficit conditions resulted in decreased growth and yield components. Moreover, when exposed to drought conditions, KDML105 was less drought-tolerant than other rice varieties. In contrast, Dro1 had the best drought tolerance, followed by IR64 and KP. However, the long growing season of KDML105, as it is a photosensitive variety, exposes it to drought risk for an extended period, affecting rice production in the long term. To avoid this unexpected feature, improving non-photosensitive varieties is a challenge that should be addressed shortly against climate risks.

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