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Critical period of weed control in aerobic rice system

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Abstract

To determine the critical period of weed control in an aerobic rice system, field trials were conducted using a quantitative series of treatments comprising of two treatments (a) weed interference (b) weed free period. The critical period was determined using Logistic and Gompertz equations. Yield of MRQ74 rice in an aerobic system would be severely impaired if weeds are not removed from 17 – 53 days after sowing (DAS). An acceptable yield loss of 5% is acceptable if weeds were controlled from 11 DAS to 74 DAS. Weeds compete significantly with AERON001 rice from 13 to 75 DAS for an acceptable 5% yield loss and 29 to 40 DAS for a 10% yield loss.

Keywords: Critical period, weed control, aerobic rice
Abbreviations: CWPC_Critical period weed control; DAS_Day after sowing; WF_weed free

Introduction

Rice is the most important irrigated crop in Asia. It occupies from 64 to 83 % net irrigated area in Southeast Asia alone (Dawe, 2004). In recent years, water scarcity worldwide has been growing due to high competition from industries, cities and the environments (Tuong et al., 2004). Thus, there was a transition from conventional transplanting to direct seeding (Dawe, 2004). Nevertheless, direct-seeding still uses a lot of water during the crop growth period. Hence, this practice is gradually being replaced by new water-saving technologies like alternate wetting and drying, bed planting and aerobic rice systems (Tuong et al., 2004). However, these methods resulted in both water savings and unacceptable yield losses especially under aerobic irrigation (Bouman, 2001). Aerobic rice systems can reduce water usage by 44% relative to transplanting method but with severe yield losses of 50 to 91% (Singh et al., 2006a).

Weed control has always been a crucial question in most water-saving irrigation technologies (Bouman, 2001). Weeds are known to compete with the crop for the same amount of limited environmental resources such as nutrients, water, light and space. Consequently, weeds are capable of reducing yield and impairing crop quality significantly (Juraimi et al., 2011). Besides, aerobic soil dry-tillage is conducive to the germination and growth of weeds. Thus, weed infestation is a major constraint in aerobic rice production and timely weed management is of paramount importance to increasing the productivity of aerobic rice (Singh et al., 2006a). The risk of yield loss from weeds in direct-seeded rice is greater than transplanted rice (Rao et al., 2007). Ramzan (2003) reported yield reduction up to 48, 53 and 74% in transplanted, direct seeded flooded and direct seeded aerobic rice, respectively. Aerobic rice is subject to much higher weed pressure with a broader weed spectrum than flood-irrigated rice (Balasubramanian and Hill, 2002).

Hand-weeding is almost impossible, costly and labour intensive in aerobic rice fields. Therefore, herbicides are considered as an easier and relevant alternative to hand-weeding (Singh et al., 2006bc). However, continuous application of herbicides throughout the season would cause a negative impact on non-target organisms, as well as development of resistant biotypes of weeds and ground water pollution (Hall et al., 1992). Thus, it is the aim of this study to develop efficient herbicide use without exploiting its optimal level. This can only be achieved by determining the critical period for weed control in aerobic irrigation. The objective of this experiment was to determine the duration of the critical period for weed control in aerobic rice system using MRQ74 and AERON001 rice varieties.

Results and discussion

Critical period for weed control of aromatic rice variety, MRQ74

Weed dry weight (kg ha^{-1})

The total weed dry weight differed significantly between treatments at probability level $p \leq 0.01$. Plots that were weedy for season-long (WM) had the significantly highest weed dry weight. Meanwhile, the lowest weed dry weight was recorded in plots that were weed-free for more than 45 days during the season such as W15, WF45, WF60 and WFM (Table 1).

Plant height (cm)

The plant heights of MRQ74 showed significant differences at all data recording times (Table 2). Treated plots W30, W60 and WM had shown to be the shortest rice plants at 30 DAS

Table 1. Weed dry weight (kg ha^{-1}) as affected by different periods of weedy and weed free conditions in MRQ74 plots.

Treatments	Weed Dry Weight (kg ha^{-1})*
W15	288.0 e
W30	3579.0 d
W45	6771.0 c
W60	16271.0 b
WM	23233.0 a
WF15	5276.0 cd
WF30	3046.0 d
WF45	631.0 e
WF60	29.0 e
WFM	0.0 e
LSD	2348.6

*Means within columns with common letters are not significantly different at P ≤ 0.05 (Protected Least Significant Different's Test)

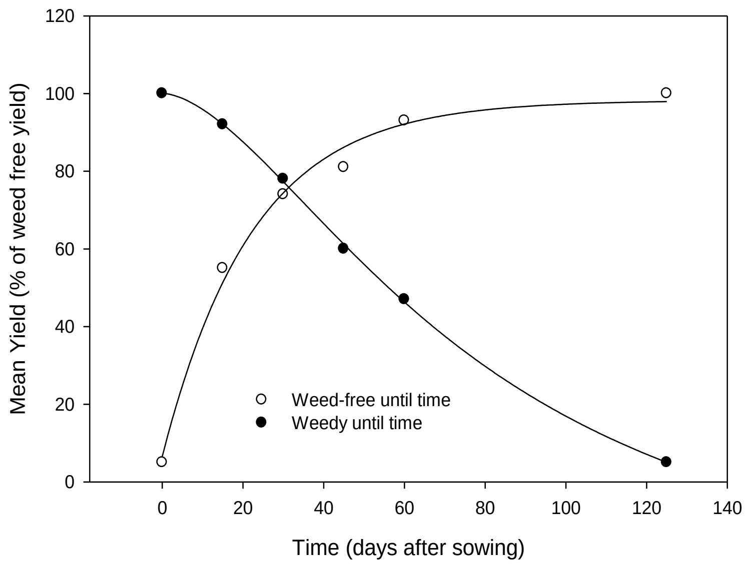

Fig 1. Yields of MRQ 74 as affected by different periods of weedy and weed free condition (Gompertz equation RY = -1779.17 + 1877.411*exp(-exp(-(x+65.7412)/21.9528)), R^2 = 0.99; Logistic equation RY = -38.0855 + 138.1273/(1+(x/78.3797)$^{1.6908}$, R^2 = 0.99. The equations were developed from mean values over replications. AYL = acceptable yield loss, RY = relative yield.

while at 60 DAS, W60 and WM plots produced the significantly shorter rice plants among all treated plots. It has been stated that rice plant height will decrease significantly if weeds are allowed to compete from 30 DAS up to harvest (Azmi, 1990). Weed growth severely increased over time, by which the rice plants in WM treatments were the shortest at 90 DAS. Begum (2006) reported that height of rice plant is significantly reduced when rice competed with *Fimbristylis miliacea* for 70 day and longer. Conclusively, rice plant height is inversely proportionate to the length of weed competition.

Number of tillers m^{-2}

Significant differences between tiller number m^{-2} of treated plots were observed at 90 DAS (Table 4). Lowest number of rice tillers counted at 90 DAS belonged to plots that were weedy up to 60 DAS, W60 (348.8) and until crop's maturity, WM (221.3). Results are in accordance with findings of Azmi (1990) who observed significant decreases in rice tiller number with weed competition from 45 DAS up to harvest. It was reported that highest relative growth rate of weeds can be found in the period from mid-tillering to panicle initiation of the rice crop (Phuong, 2001). On average, 881.1 tillers m^{-2} was produced in plots at 90 DAS.

Yield and yield components

The weight of a thousand MRQ74 grains was not significantly influenced by different treatments although they numerically differed among themselves. Nonetheless, the biggest weight was recorded in W60 (18.4), while the smallest weight in W15 (16.9). Similar finding was also reported by Ahmed et al. (2008), where the weed control treatments did not affect 1000-grain weight but significantly increased the grain yield.

Analysis of the number of spikelets per panicle of MRQ 74 showed significant difference only for W60 and Wm treatments. Rice plants that competed with weeds until 60 DAS and crop's maturity resulted in the significantly lowest number of spikelets per panicle; 55 and 39, respectively. The rest of the treated plants did not show any significant differences (Table 4). Crop-weed competition for nitrogen could reduce the number of spikelets produced by retarding the growth rate of differentiating panicles delaying the initiation time of spikelets and; thereby, reduce the duration of spikelet initiation (Coaldrake and Pearson, 1985). Reductions in rice grain yield per panicle due to season-long weed competition have been previously reported by Begum et al. (2008).

Grain yield from plots that were weed-free until crop maturity surpassed those from plots that were weedy the entire season by almost 1904 % (Table 5). Reports of rice yield increment compared to control plots have been reported as much as 144% by Chin et al. (2007). In the present trials, severe weed canopy cover, during critical grain-filling period in WM plots, severely reduced the yield to 127 kg ha^{-1}. Grain yield was also observed to decrease significantly as weedy durations increased.

Critical period for weed control

The Logistic and Gompertz equations were fitted to develop a graph (Fig 1) to determine the critical period for weed control. The estimated critical period for an acceptable yield loss of 5% was 11 – 74 DAS. Meanwhile, the estimated critical period for an acceptable yield loss of 10% was 17 – 53 DAS. In total, the length of time for weed removal and crop-weed competition are the two most vital factors in determining critical period for weed control. Weediness and rice yield parameters were not the only evidence of critical period. Other parameters like number of spikelets per panicle and number of rice tiller per hill were also defined the existence of the critical period.

Critical period for weed control using aerobic rice nursery Line, AERON001

Weed flora

The major weeds that existed in the experimental troughs with descending predominance were *Leptochloa chinensis* (L.) Nees > *Echinochloa crus-galli* > *Fimbristylis miliacea* (L.) Vahl > *Ludwigia octovalvis* > *Echinochloa colona* (L.) Link > *Cyperus iria* L. > *Digitaria adscendens* (H. B. K. Henr.) > *Monochoria vaginalis*.

The data recorded on the weed population and its dry weight is presented in Table 8. It is clear from the data that different length and time of weedy conditions significantly affected weed populations in this study. Weeds were still emerging after 30 days and before 45 DAS (WF30) at 313 weeds m^{-2} and weighed 336.1 g at rice maturity after 75 DAS. However, there was no weed emergence at 45 DAS and onwards (WF45, WF60 and WFM). An equal numbers of weeds were detected when the weeds were left to grow until 45 (W45) and further until 60 DAS (W60), amounting to 935 and 956 weed plnats, respectively. Annual weeds with short life cycle around 45 days seemed to inhabit the experimental soil media.

Treatments that were left weedy until 60 DAS (W60) and maturity (WM) and weed-free until 15 DAS (WF15) had the significantly highest weed dry weight (Table 6). This is due to their growth period being the longest among all treatments. These troughs were infested with 79 to 85 % of mature *Leptochloa chinensis*

Logically, treatments that were left weedy until 60 DAS (W60) and maturity (WM) and weed-free until 15 DAS (WF15) had the significantly highest weed dry weight (Table 6). This is due to their weedy period being the longest among all treatments. In fact, these troughs were infested with 79 to 85 % of matured *Leptochloa chinensis*.

Meanwhile, the trough that was weedy until 15 DAS (W15) gave the significantly lowest weed dry weight (1.6) and was dominated by *Leptochloa chinensis* and *Fimbristylis miliacea* seedlings. The variation in weed dry weight can be attributed to the different stages of weed growth at the time of data recording. Bhan (1983) reported that maximum weed competition occurred during early crop growth stage with weed dry matter production exceeding from the upland rice. Meanwhile, weed dry matter production in lowland rice increased up to 60 days after transplanting but never exceeded from the crop.

Plant height (cm)

Observation on crop height growth did not show any significant differences at any period (Table 7) due to low weed biomass at early growth stages. The height and the number of tillers of rice plant were the same in all treatments due to low weed biomass at early stage. However, there was a significant negative correlation (r^2 = 0.87) between plant height at 75 DAS and weed dry weight. Increasing weedy-duration treatments gradually reduced the plant height. The tallness of AERON001 rice plants or even their responsiveness to fertilizers could be the possible reasons of the plants not being significantly impacted by the presence of weed.

Number of tiller m^{-2}

A significant decrease in the number of rice tillers was observed at 50 DAS, when rice plants competed with weeds for 60 DAS (W60) and season-long (WM). This could be attributed to the crop-weed competition for space (Table 8). It has been noted that rice plant height was reduced by competition with jungle rice (*Echinochloa colona*), and the reduction was intensified with increased weed density (Chauhan and Johnson, 2010).

Yield and yield components

All data recorded on yield components produced significant differences except for the weight of a thousand grains. There were significant differences in the panicle lengths, number of spikelets per panicle and filled panicles between the season-long weedy and weed-free treatments (Table 9). The plants that were weed-free until maturity had the longest panicles (29.8), while those were left weedy until 60 DAS had the shortest panicles (25.6), similar to those that were left weedy until 45 DAS (W45) and maturity (WM). Weed controlling started from the day of sowing seemed to have a positive impact on panicle length. Plants that competed with weeds until 60 DAS and maturity resulted in the significantly lowest number of spikelets per panicle as 126 and 118, respectively. These amounts were also similar to the plants that were weedy until 45 DAS. The highest number of spikelets per panicle was obtained from plants that were weed-free for the entire season (167) and was not significantly different from the rest of the treatments.

The same trends were found in filled grains $panicle^{-1}$ between weedy and weed-free treatments. However, the highest filled grains $panicle^{-1}$ (81.4) was found in panicles of plants that were weedy until 45 DAS and the lowest (66.6) in season-long weedy treatment as predicted (Table 9). Data showed that when the plants were weedy for more than 60 days during the growth (W60, WM, WF15), there was yield reduction of about 66 to 83 %. In contrast, pots that were weed-free for more than 45 days (W15, W30, WF30, WF45,

Table 2. Plant height (cm) of MRQ74 rice plants as affected by different periods of weedy and weed-free conditions.

Treatments	Time of observation (DAS)*		
	30	60	90
W15	41.8 a	88.3 a	101.6 ab
W30	33.2 d	74.4 c	95.1 bc
W45	40.1 ac	77.7 c	88.2 c
W60	37.4 cd	54.3 d	72.0 d
WM	34.9 cd	54.8 d	58.9 e
WF15	42.2 a	84.1 ac	93.1 bc
WF30	43.5 a	95.0 a	108.0 a
WF45	44.7 a	91.0 a	104.2 ab
WF60	43.0 a	91.8 a	107.3 a
WFM	42.2 a	95.3 a	110.2 a
LSD	5.63	12.52	11.33

* Means within columns with common letters are not significantly different at $P \leq 0.05$ (Protected Least Significant Different's Test).

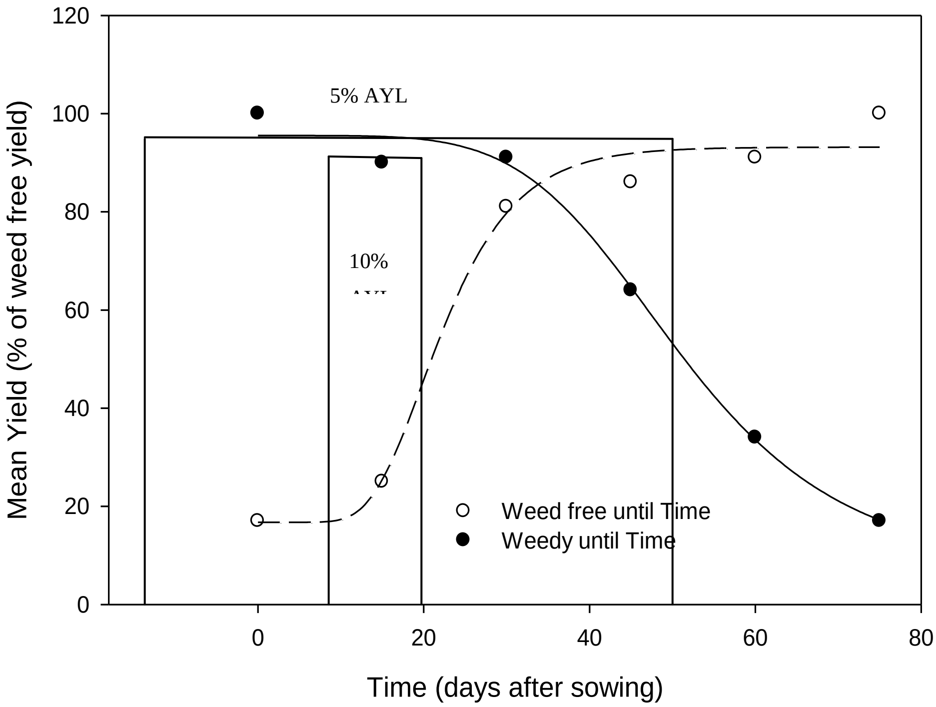

Fig 2. Yields of AERON001 as affected by different periods of weedy and weed free condition (Gompertz equation RY = 16.7575 + 76.4192*exp(-exp(-(x-19.8235)/6.1962)), R^2 = 0.99; Logistic equation RY = 5.8158 + 89.7079/(1+(x/51.1323)$^{5.0335}$, R^2 = 0.99. The equations were developed from mean values over replications. AYL = acceptable yield loss, RY = relative yield

WF60, WFM) during its life cycle produced significantly higher grain yields from the former. Overall, grain yield decreased significantly when weed competition prevails until 45 days (W45) as compared to that of the control treatment. Reasonably, grain yield decreased when the weedy periods were increased and vice versa (Table 10).

Determination of weed control critical period

Predicted and observed mean rice yields as affected by different periods of weedy and weed-free conditions are shown in Fig 2. The critical time of weed removal in rice, computed using the Logistic regression equation, was decreased like the pre-determined acceptable yield loss level of 10 to 5 %. The end of critical period for weed control in aerobic rice, using the Gompertz regression equation, increased as the acceptable yield loss of 10 to 5 %. A 5% yield loss is often considered as an arbitrary standard for determining the critical period for weed control in rice cultivation (Begum et al., 2008). However, the acceptable yield loss can be adjusted according to the cost of weed control and the expected financial gain (Knezevic et al., 2002).

From this experiment, it is clear that the critical period for weed control in aerobic rice was centered around 30 to 45 days of rice plant growth stage. In this case, AERON001 with a 75 days maturity period had significant competitions from 13 to 75 DAS for a 5% acceptable yield loss and 29 to 40 DAS for a 10% acceptable yield loss.

Comparison between MRQ74 and AERON001

The duration of critical periods for weed control at 10% acceptable yield losses for both varieties seemed to differ by two folds. The length of time to control weeds in aerobic system of MRQ 74 rice variety was longer (36 days) than the

Table 3. Number of MRQ74 rice tillers m^{-2} at 90 DAS as affected by different periods of weedy and weed-free conditions.

Treatments	Tillers m^{-2} *
W15	1137.5 ab
W30	907.0 bc
W45	720.0 c
W60	348.8 d
WM	221.3 d
WF15	917.5 bc
WF30	1217.5 a
WF45	1093.8 ab
WF60	1107.5 ab
WFM	1140.0 ab
LSD	249.86

*Means within columns with common letters are not significantly different at P ≤ 0.05 (Protected Least Significant Different's Test).

Table 4. Yield components of MRQ74 as affected by different periods of weedy and weed free conditions.

Treatments	Weight of 1000 grains (g)*	Number of spikelets per panicle*
W15	16.88 a	72.88 a
W30	17.20 a	71.18 a
W45	17.68 a	72.13 a
W60	18.40 a	55.03 b
WM	17.40 a	39.40 c
WF15	17.45 a	73.88 a
WF30	17.08 a	82.58 a
WF45	16.85 a	69.45 a
WF60	17.38 a	77.93 a
WFM	17.05 a	78.78 a
LSD	1.06	14.38

*Means within columns with common letters are not significantly different at P ≤ 0.05 (Protected Least Significant Different's Test).

one of AERON001 aerobic rice variety that only needed 10 weed-free days. Time of weed emergence was reported to influence the critical period for weed control for a given crop (Knezevic et al., 2002). In this case, weeds in AERON001 study emerged later than two weeks after sowing. This was in contrast to those of which in MRQ 74 that emerged as early as 3 DAS.

This could possibly be attributed to the different maturity periods of both varieties. The longer the maturity of a crop, the longer the weed interference would become. Hence, the critical period of crop-weed interaction would need to be prolonged. Nevertheless, CPWC is highly variable and dependent on the relationship between crop seeding date and weed emergence at a place (Martin et al., 2001). The critical period for weed control is reportedly unique for every crop due to species-specific differences in morphology, physiology and development (Knezevic et al., 2002).

Consequently, the gathered data between flooded rice variety MRQ 74 and aerobic rice nursery line AERON001 varied slightly. This is especially true for 10% yield loss. However, the almost comparable critical period results for an acceptable yield loss of 5% may be the product of implementing similar experimental conditions such as fertilizer application, irrigation technique and other cultural practices.

Comparison between MRQ74 and AERON001

The duration of critical periods for weed control at 10% acceptable yield losses for both varieties seemed to differ by two folds. The length of time to control weeds in aerobic system of MRQ 74 rice variety is longer (36 days) than AERON001 aerobic rice variety that only needed 10 weed-free days. Time of weed emergence was reported to influence the critical period for weed control for a given crop (Knezevic et al., 2002). In this case, weeds in AERON001 study emerged later than two weeks after sowing. This was in contrast with MRQ 74 that emerged as early as 3 DAS. This could possibly be attributed to the different maturity periods of both varieties. The longer the maturity of a crop, the longer the weed interference would become. Hence, the critical period of crop-weed interaction would need to be prolonged. Nevertheless, CPWC is highly variable and dependent on the relationship between crop seeding date and weed emergence at a place (Martin et al., 2001).

Materials and methods

Location

Experiments on MRQ74 and AERON001 rice varieties were carried out consecutively at Malaysian Agricultural Research and Development Institute (MARDI), Seberang Perai, Penang, Malaysia, in an open net experimental plant house. Meteorological data was sourced from Malaysian Meteorological Department, based on data collected from the MARDI Seberang Perai station itself (Latitude: 05° 21'N, Longitude: 100° 24'E, Above Mean Sea Level: 1.5 m). The annual rainfalls during the period of study were 2478 mm and 2088 mm, respectively. Crops received 770.2 mm rainfall on 69 occasions. Temperature fluctuated between 26.9 and 28 ^{0}C during the experimental duration.

Planting materials

The seed sample of a local aromatic rice variety MRQ 74 was obtained from MARDI. The MRQ74 seeds were sown in three rows with inter-row spacing of 20 cm at 100 kg ha^{-1} seed rate. The seed rate in this experiment was 40 kg ha^{-1}, which fulfilled the recommended rate for aerobic rice cultivation ranging from 40 kg ha^{-1} to 60 kg ha^{-1} (Singh and Chinnusamy, 2006).

Table 5. Grain yield (kg ha^{-1}) of MRQ74 as affected by different periods of weedy and weed free conditions.

Treatments	Grain Yield (kg ha^{-1})*	Relative Yield (%)*	Yield Increment (%)*
W15	2342.5 a	92.00	1744.12
W30	1985.7 acd	77.99	1463.24
W45	1528.0 cde	60.01	1102.94
W60	1196.8 e	47.00	842.16
WM	127.0 f	4.99	0.00
WF15	1399.8 de	54.98	1001.96
WF30	1892.3 cd	74.32	1389.71
WF45	2062.3 ac	81.00	1523.53
WF60	2368.0 a	93.01	1764.22
WFM	2546.1 a	100.00	1904.41
LSD	638.61	-	-

*Means within columns with common letters are not significantly different at $P \leq 0.05$ (Protected Least Significant Different's Test)

Table 6. Weed population (m^{-2}) and weed dry weight (g m^{-2}) as affected by different periods of weedy and weed free conditions in AERON001 plots.

Treatments	Weed Population (plants m^{-2})*	Weed Dry Weight (g m^{-2})*
W15	437.1 cd	1.6 c
W30	1059.8 a	143.2 c
W45	934.6 ab	1204.0 b
W60	955.8 ab	1761.6 a
WM	661.3 bc	2031.1 a
WF15	530.5 cd	1850.0 a
WF30	313.2 de	336.1 c
WF45	0.0 e	0.0 c
WF60	0.0 e	0.0 c
WFM	0.0 e	0.0 c
LSD	337.07	548.0

DAS: Days after Sowing; * Means within columns with common letters are not significantly different at $P \leq 0.05$ (Protected Least Significant Different's Test).

Table 7. Plant height (cm) of AERON001 rice plants as affected by different periods of weedy and weed-free conditions.

Treatments	Time of observation (DAS)*		
	25	50	75
W15	65.0 a	137.5 a	141.3 a
W30	67.2 a	133.6 a	135.0 a
W45	75.3 a	136.5 a	134.2 a
W60	67.0 a	130.3 a	128.6 a
WM	65.8 a	125.2 a	126.3 a
WF15	67.9 a	134.3 a	129.6 a
WF30	67.2 a	139.3 a	134.3 a
WF45	67.9 a	135.0 a	133.4 a
WF60	66.5 a	139.8 a	140.2 a
WFM	70.2 a	144.9 a	140.4 a
LSD	11.2	12.0	10.3

DAS: Days after Sowing; * Means within columns with common letters are not significantly different at $P \leq 0.05$ (Protected Least Significant Different's Test).

Soil preparation

Soil from a dry land in the station was thoroughly filled into fiber troughs measured at 73 cm of length, 55 cm of width and 45 cm of height. The soil in the experiment site belonged to Sogomona series with average pH of 4.32. The organic matter (OM) content and cation exchange capacity (CEC) of the soil were 1.1 % and 5.6 meq/100 g soil, respectively. Total N was 0.04%, while the available P was 91.41 ppm. Exchangeable K, Ca and Mg were 0.42, 1.39 and 0.52 meq/100 g soil accordingly.

Crop Management

Fertilizers were applied according to the Interim Fertilizer Rate Recommended for Aerobic Rice at 180 kg ha^{-1} N: 54 kg ha^{-1} P_2O_5: 76.5 kg ha^{-1} K_20 (Sariam Othman, 2010). 18.1g of NPK Blue granules per trough were applied at 5 days after emergence (DAE). This was followed by two more urea application of 4.71g at 18 and 30 DAE and lastly 1.59g at 42 DAE. The troughs were maintained under non-saturated aerobic condition throughout the experiment duration. The watering carried out once every day using a hosepipe. Troughs have also been drilled with small holes at the bottom to avoid ponding during rainy days. No herbicide was used and instead, hand-weeding technique was undertaken daily during the required periods of each of the above treatments. Weeds were uprooted manually. Insecticide etofenprox 10% (TREBON 10EC) and fungicide difenoconazole 25% (SCORE 25EC) to control leaf folder and leaf blast, respectively, were only used whenever necessary. Three units of jet fill tensiometers of 30 cm body-length were installed in random troughs to monitor soil suction value or subsurface water tension of an aerobic system on a regular basis.

Table 8. Number of AERON001 rice tillers m^{-2} as affected by different periods of weedy and weed-free conditions.

Treatments	Time of observation (DAS)*		
	25	50	75
W15	463.3 a	527.4 ab	514.3 a
W30	460.8 a	533.0 ab	496.3 a
W45	533.0 a	458.9 b	485.7 a
W60	446.5 a	333.8 c	386.1 b
WM	375.5 a	308.9 c	290.8 c
WF15	449.0 a	361.8 c	341.2 bc
WF30	493.2 a	546.1 ab	510.0 a
WF45	526.2 a	590.3 a	533.6 a
WF60	464.5 a	579.7 a	537.4 a
WFM	538.6 a	594.1 a	539.9 a
LSD	170.51	92.53	66.31

DAS: Days after Sowing; * Means within columns with common letters are not significantly different at $P \leq 0.05$ (Protected Least Significant Different's Test).

Table 9. Yield components of AERON001 as affected by different periods of weedy and weed free conditions.

Treatments	Weight of 1000 grains (g)*	Number of spikelets per panicle*	Filled Grains $Panicle^{-1}$ *	Panicle Length (cm)*
W15	26.4 a	165.0 a	73.2 bcd	28.9 abc
W30	26.9 a	153.3 a	79.8 ab	28.8 abc
W45	27.5 a	132.0 bc	81.4 a	27.0 cd
W60	26.7 a	125.5 c	73.3 bcd	25.6 d
WM	26.5 a	118.3 c	66.6 d	27.1 bcd
WF15	26.4 a	147.3 ab	66.7 d	29.3 ab
WF30	26.4 a	165.0 a	70.9 cd	29.1 abc
WF45	27.2 a	153.3 a	72.5 bcd	28.7 abc
WF60	26.4 a	165.3 a	77.8 abc	29.3 abc
WFM	26.9 a	166.5 a	75.7 abc	29.8 a
LSD	1.7	20.8	7.8	2.3

DAS: Days after Sowing; * Means within columns with common letters are not significantly different at $P \leq 0.05$ (Protected Least Significant Different's Test).

Table 10. Grain yield (kg ha^{-1}) of AERON001 as affected by different periods of weedy and weed free condition.

Treatments	Grain Yield (kg ha^{-1})*	Relative Yield (%)*	Yield Increment (%)*
W15	6673 ab	90	433.4
W30	6748 ab	91	439.4
W45	4738 bc	64	278.7
W60	2549 cd	34	103.8
WM	1251 d	17	0.0
WF15	1892 d	25	51.2
WF30	6044 ab	81	383.1
WF45	6422 ab	86	413.4
WF60	6775 ab	91	441.6
WFM	7440 a	100	494.7
LSD	2409.2	-	-

DAS: Days after Sowing; * Means within columns with common letters are not significantly different at $P \leq 0.05$ (Protected Least Significant Different's Test).

Experimental design

The experimental design was a randomized complete block with four replications. To determine critical period of weed control, a quantitative series of treatments comprising two components (a) increasing duration of weed interference and (b) increasing length of weed-free period were imposed.

Treatments

Ten treatments were devised to examine the effects of differing periods of weed control and weed interference, and were similar to those of Nieto et al. (1968). The treatments were: W15: Weedy until 15 days after sowing (DAS) followed by weed-free until crop's maturity, W30: Weedy until 30 DAS followed by weed-free until crop's maturity, W45: Weedy until 45 DAS followed by weed-free until crop's maturity, W60: Weedy until 60 DAS followed by weed-free until crop's maturity, WM: Weedy from sowing to crop's maturity, WF15: Weed-free until 15 DAS followed by weedy until crop's maturity, WF30: Weed-free until 30 DAS followed by weedy until crop's maturity, WF45: Weed-free until 45 DAS followed by weedy until crop's maturity, WF60: Weed-free until 60 DAS followed by weedy until crop's maturity, WFM: Weed-free from sowing to crop's maturity.

Data collection

Weed dry weight

Weed samples were collected at the end of each weed interference period. Weeds consisting of grasses, broadleaves and sedges were counted according to species and dried under the sun before being dried in an oven at 70˚C for 48 hours and then weighed.

Growth and yield parameters

The plant height and tiller number for MRQ74 were recorded at 30, 60 and 90 DAS and at 25, 50 DAS and at harvest (75 DAS) for AERON001. Differing assessment days for MRQ 74 and AERON001 are due to different maturity periods for the two rice varieties. Other parameters recorded at harvest were: the number of panicles per hill, number of spikelets per panicle, number of filled and empty grains per panicle, spikelet sterility, panicle length, grain yield and 1000-grain weights.

Critical period for weed control (CPWC)

Sigma Plot software was used to develop the critical period graph and to determine the critical period value for 5 % and 10 % acceptable yield losses (AYL). Relative yield data for the weedy and weed-free treatments were regressed against the increasing duration of weed interference or increasing length of the weed-free period. The logistic equation was used to determine the beginning of CPWC while the Gompertz equation was used to determine the end of CPWC.

Statistical analysis

The SAS statistical software (SAS, 2003) was used to analyze the data, including analysis of variance (ANOVA) and comparison of means based on a protected LSD procedure.

Conclusion

This study portrays the significance of CPWC determination for sustainable weed management in aerobic rice. The practical implication of this study is that under the similar experimental conditions aerobic rice field should be kept weed-free during 17- 53 DAS. An acceptable yield loss at 5% could be accepted if weeds were controlled from 11 DAS to 74 DAS. Weeds compete significantly with AERON001 rice from 13 to 75 DAS for an acceptable 5% yield loss and 29 to 40 DAS for a 10% yield loss. Since weeds emerge after this period are supposed to cause no substantial yield loses, the need for applying additional herbicides or weeding more than 2 times, as practiced by most farmers could be avoided, which lead to significant cost savings. Nevertheless, weed management can be extended beyond that period if the objective is not only to have higher yield but also to avoid weed seed rain to prevent build-up of the weed seed bank, which is of major concern for long-term sustainability of weed management.

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