Sains Malaysiana 53(7)(2024): 1525-1532
http://doi.org/10.17576/jsm-2024-5307-04

Inhibition of Pre-Emergent Herbicide on Weedy Rice under Flooded and Saturated Soil Conditions in Rice

(Perencatan Racun Rumpai Pra-Cambah pada Padi Angin di bawah Keadaan Banjir dan Tanah Tepu pada Padi)

Dilipkumar Masilamany[1,*], Erwan Shah Shari[1], Nurul Nahar Esa[1], Site Noorzuraini abd Rahman[2] & Chuah Tse Seng[3]

[1]*Rice Research Centre, Malaysian Agricultural Research and Development Institute (MARDI), MARDI Seberang Perai, 13200 Kepala Batas, Pulau Pinang, Malaysia*
[2]*Agrobiodiversity and Environmental Research Centre, Malaysian Agricultural Research and Development Institute (MARDI), MARDI Seberang Perai, 13200 Kepala Batas, Pulau Pinang, Malaysia*
[2]*Faculty of Plantation and Agrotechnology, Universiti Teknologi MARA, Perlis Branch, Arau Campus, 02600 Arau, Perlis, Malaysia*

Received: 18 August 2023/Accepted: 4 June 2024

ABSTRACT

Weedy rice poses a formidable challenge in rice cultivation due to its genetic similarity to cultivated rice, making selective herbicides less effective in controlling it without causing harm to the cultivated rice. The potential use of pre-emergent herbicides before rice sowing to inhibit emergence and growth of weedy rice seedlings in the soil remain unknown. Thus, this study aimed to evaluate the responses of weedy rice towards selected pre-emergent herbicides under different soil water conditions and to identify the optimal timing for rice seed sowing following the application of pre-emergent herbicide to the soil under glasshouse conditions. The results showed that oxadiazon and pretilachlor at 500 g ai ha^{-1} exhibited higher reductions in weedy rice density and dry weight compared to those given by pendimethalin. Under saturated soil conditions, oxadiazon demonstrated 79 and 80% reductions whereas pretilachlor gave 50 and 59% reductions in weedy rice density and dry weight, respectively. By contrast, under flooded soil conditions both oxadiazon and pretilachlor resulted in complete inhibition of weedy rice. The study showed that delaying rice seed sowing for at least six days after application of pretilachlor or oxadiazon effectively minimized phytotoxic effects on rice. These findings provide valuable insights on the impact of soil water conditions when applying pretilachlor and oxadiazon for effective weedy rice control in direct-seeded rice systems.

Keywords: Direct seeded rice; land preparation; oxadiazon; pendimethalin; pretilachlor; weedy rice

ABSTRAK

Padi angin mengundang cabaran yang hebat dalam penanaman padi kerana persamaan genetik dengan padi yang ditanam, menjadikan sesetengah racun rumpai kurang berkesan dalam mengawalnya tanpa mencederakan padi yang ditanam. Potensi penggunaan racun rumpai pra-cambah sebelum menanam padi untuk menyekat percambahan dan pertumbuhan biji benih padi angin di dalam tanah masih tidak diketahui. Penyelidikan ini mengkaji potensi penggunaan beberapa racun rumpai pra-cambah pada kadar dan keadaan air tanah yang berbeza untuk mengawal padi angin. Hasil kajian menunjukkan bahawa oksadiazon dan pretilachlor pada 500 g ai ha^{-1} menunjukkan perencatan yang lebih tinggi dalam kepadatan dan berat kering padi angin berbanding dengan rawatan pendimetalin. Di bawah keadaan tanah air tepu, oksadiazon mencatat 79 dan 80% perencatan manakala pretilachlor mencatat 50 dan 59% perencatan masing-masing dalam kepadatan dan berat kering padi angin. Sebagai perbandingan, di bawah keadaan tanah air takung, kedua-dua oksadiazon dan pretilachlor merencat sepenuhnya pertumbuhan padi angin. Kajian ini menunjukkan bahawa menangguhkan taburan biji benih padi sekurang-kurangnya enam hari selepas aplikasi pretilachlor atau oksadiazon akan mengurangkan kesan fitotoksik padi. Hasil kajian ini memberikan maklumat penting mengenai kesan keadaan air tanah semasa mengaplikasi pretilachlor dan oksadiazon untuk kawalan padi angin yang berkesan dalam sistem padi tabur terus.

Kata kunci: Oksadiazon; padi angin; padi tabur terus; pendimetalin; penyediaan tanah; pretilachlor

INTRODUCTION

Rice is a crucial staple food for more than half of the world's population, and this number is anticipated to rise up to 25% by 2050, according to Samal et al. (2022). There are two primary methods for planting rice: direct-seeding and transplanting. In direct seeding, rice seeds are sown and sprouted directly into the field, whereas transplanting involves replanting rice seedlings grown in nurseries into puddled soils. As rice transplanting necessitates a lot of labor and water, many rice farmers have turned to direct-seeding, which requires fewer inputs. As a result, direct-seeding is becoming more prevalent among rice growers, especially in countries such as Japan, China, the United States, Malaysia, Sri Lanka, Cambodia, the Philippines, Vietnam, and Thailand (Chaudhary et al. 2022; Su et al. 2022).

The direct seeding rice system has proven to be effective in conserving irrigation water, but it has also led to increased competition between crops and weeds. Rice plants and weeds grow together under aerobic conditions, which results in a greater incidence of weed infestation. Several studies have highlighted that weed infestation can lead to significant yield losses in direct-seeded rice, ranging from 40 - 100%. For instance, a study conducted in India showed that uncontrolled weeds in direct-seeded rice reduced grain yield by 85-98% (Singh et al. 2011). Similarly, in Malaysia, yield losses of 60% have been attributed to weed competition in direct-seeded rice (Karim, Man & Sahid 2004). Another study in Bangladesh found that weed infestation caused yield losses of 40-100% in direct-seeded rice (Ahmed, Salim & Chauhan 2014).

Among the various weed species found in direct-seeded rice fields, weedy rice poses the most significant challenge for several reasons. Firstly, weedy rice and cultivated rice have similar physiological and morphological traits, making it difficult to be identified at the critical stages of weeding (Dilipkumar et al. 2021). Secondly, weedy rice has a higher competitive ability than other weeds in rice fields, enabling it to compete effectively with rice crops for essential resources such as water, nutrients, and light (Kumar & Ladha 2011). This competition leads to lower yields and poor quality of rice. Thirdly, weedy rice has a high level of seed dormancy, enabling its seeds to remain in the soil for an extended period and still germinate (Tseng et al. 2013). Fourthly, weedy rice can shatter before harvest, which makes it challenging to control using mechanical methods such as hand weeding or tillage. Additionally, this shattering tendency also allows weedy rice seeds to spread easily to other fields, contributing to its spread and persistence (Ziska et al. 2015). Finally, weedy rice is an adaptable plant that can thrive in diverse environmental conditions such as temperature, water availability, and soil types, allowing it to persist and spread in rice fields, even under adverse conditions (Li et al. 2017).

Weedy rice is genetically similar to cultivated rice, making it difficult to control using selective herbicides without harming the cultivated rice. Therefore, to manage weedy rice in direct-seeded rice systems, chemical control measures must be taken before sowing the cultivated rice. A period of fallow can be implemented to allow the weedy rice to germinate, followed by its eradication using non-selective herbicides. Additionally, the application of pre-emergent herbicides immediately after tillage under flooded conditions has been shown to effectively manage weedy rice (Olajumoke et al. 2016). Pre-emergent herbicides function by establishing a chemical barrier in the soil to inhibit the emergence of weed seedlings. Common pre-emergent herbicides used in rice farming include pretilachlor, oxadiazon, and pendimethalin. Nevertheless, the potential of these herbicides applying under standing water conditions in order to control weedy rice emergence before rice sowing requires further study. Pretilachlor is a pre-emergent herbicide that inhibits lipid synthesis in weed seedlings, thereby preventing the growth of grasses, sedges and some broadleaf weeds. Oxadiazon and pendimethalin are pre-emergent herbicides that inhibit the synthesis of carotenoids and cell division, respectively, in weed seedlings, thereby preventing the growth of a wide range of annual grasses and broadleaf weeds. Proper application of these herbicides at the right time and rate is important for optimal weedy rice control and to avoid any adverse effects on rice plants. Therefore, this study aimed to 1) evaluate the responses of weedy rice towards pretilachlor, oxadiazon, and pendimethalin at different rates, 2) investigate inhibitory effects of pretilachlor and oxadiazon on weedy rice under different soil water conditions, and 3) identify the optimal timing for rice seed sowing following the application of pretilachlor or oxadiazon to the soil.

MATERIALS AND METHODS

The study was conducted at the Weed Science Glasshouse, Rice Research Centre, MARDI Seberang Perai, Pulau Pinang, Malaysia. Weedy rice seeds with an easy shattering variant (Reference number: MRGB11544) were obtained from the Rice Genebank of MARDI Seberang Perai, Pulau Pinang, Malaysia. This variant was selected based on its dominance in the Malaysian rice field.

HERBICIDE AND APPLICATION RATE EFFECTS ON WEEDY RICE

Three pre-emergent herbicides, namely pretilachlor, oxadiazon, and pendimethalin, were selected for evaluation in this study. The recommended field rate for each herbicide was 500 g ai ha^{-1}. In addition to the recommended field rate, two additional rates were included in the treatment list, corresponding to half (250 g ai ha^{-1}) and twice (1000 g ai ha^{-1}) the recommended field rate. This resulted in a total of three rates being evaluated for each herbicide. Twenty pre-germinated weedy rice seeds were sown in plastic pots (19 cm diameter × 26 cm height) filled with 1.6 kg of moist silty loam field soil per pot (comprising 21% clay, 75% silt, 4% sand, pH 6, and 1.6% organic carbon). The seeds were sown at a depth of 0.5 cm. The pots were placed on the center benches in a glasshouse exposed to natural sunlight with a day/night temperature of 35/20 °C. One day after sowing, all pots were irrigated until the water level reached a height of 2 cm above the soil surface. The herbicides were sprayed under these standing water conditions using a knapsack sprayer equipped with a flat-fan nozzle, delivering 200 L ha^{-1} at a spray pressure of 100 kPa. Throughout the experiment, the pots were irrigated as needed to maintain the standing water level. As a control treatment, tap water was used. The treatments were arranged in a factorial completely randomized block design with five replications, where two factors, namely type of herbicide and application rate were involved and the experiment was repeated twice. At seven days after treatment, the number of seedling emergence was counted (plant density) and shoot dry weight was measured. Seedlings were considered emerged when the plumule lengths were >2 mm. The shoot dry weight was determined by harvesting the aboveground living tissues of healthy plants, followed by drying them at 80 °C for 72 h. The data on plant density and shoot dry weight were expressed as percentages relative to their respective controls.

HERBICIDE AND SOIL WATER CONDITION EFFECTS ON WEEDY RICE

Once the potential herbicide and effective rate for inhibiting weedy rice were identified, a subsequent experiment was conducted to assess the impact of soil water conditions on the herbicide efficacy. The pot experiment followed the same procedure as the previous experiment. Each pot was treated with selected pre-emergent herbicides at a rate of 500 g ai ha^{-1}. Control pots were treated with tap water. Two different soil water conditions were implemented: saturated and standing water conditions. The treatments were arranged as factorial in completely randomized block design with five replications where factor one was type of herbicide while factor two was soil water condition and it was repeated twice. Seven days after the treatment, density and dry weight of weedy rice were evaluated and data were presented as described earlier.

HERBICIDE AND SOWING TIME EFFECTS ON CULTIVATED RICE

To determine the appropriate timing for sowing rice seeds and avoid any phytotoxic effects, a pot experiment was conducted under glasshouse conditions. Plastic pots with dimensions of 19 cm diameter and 26 cm height were filled with 1.6 kg of moist silty loam field soil per pot. The soil composition comprised 21% clay, 75% silt, and 4% sand, with a pH of 6 and 1.6% organic carbon content. The pots were subjected to selected pre-emergent herbicides at a rate of 500 g ai ha^{-1} under standing water conditions. The water level in the pot was maintained until sowing the rice seeds. The herbicides were sprayed using a knapsack sprayer equipped with a flat-fan nozzle, delivering 200 L ha^{-1} at a spray pressure of 100 kPa. The experiment included a control treatment with soil that was not treated with herbicides. The rice tolerance levels towards the pre emergent herbicides were determined by sowing twenty pre-germinated rice seeds (MR297) at 3, 6, and 12 days after herbicide treatment. MR297 was selected because it is a current popular variety cultivated in Malaysia. The soil water level in each pot was maintained under saturated conditions just before sowing the rice seeds. Each pot was irrigated to standing water level started from day 10 after sowing. The experiment included a control treatment with soil that was not treated with herbicides. The phytotoxic activity of herbicide was conducted in five replicates and arranged in a factorial completely randomized design where factor one is type of herbicide while factor two is rice sowing time and it was repeated twice. Rice density and dry weight were measured at day 30 after sowing. Density was recorded based on the number of seeds with emerged shoots, and the shoot dry weight was determined by harvesting above ground living tissues remaining of each seedling, drying them at 80 °C for 72 h, and followed by weighing. All data were expressed as percentages relative to their respective controls.

STATISTICAL ANALYSIS

All data were checked for homogeneity of variance and normality before being subjected to two-way ANOVA using SAS version 9.4 (SAS Institute Inc., Cary, NC). Since data from the respective repeated experiments were not significantly different, data were pooled and combined. The Tukey test was used to compare the mean among the treatments at 5% of significant level.

RESULTS AND DISCUSSION

EFFECTS OF HERBICIDES AND APPLICATION RATES ON WEEDY RICE

The results showed significant variations in both density and dry weight of weedy rice among different herbicides and application rates tested. Since no herbicide type-by-application rate interaction was observed on weedy rice dry weight, data were pooled over and main effects are presented (Table 1). The results showed significant variations in both density and dry weight of weedy rice among different herbicides and application rates tested (Table 1). The dry weight of weedy rice plants treated with oxadiazon or pretilachlor were reduced by 92 and 95%, respectively, compared to those treated with pendimethalin which had only 68% reduction averaged across herbicide rate. When averaged across herbicide type, the dry weight of weedy rice decreased significantly with increasing herbicide rate. Weedy rice treated with 250 g ai ha^{-1} exhibited dry weight reduction of 69%, while the dry weight significantly reduced by 90% when treated with 500 g ai ha^{-1} and experienced an even greater reduction of 95% when treated with 1000 g ai ha^{-1}. However, there was no significant difference ($p>0.05$) in dry weight between the treatments of 500 g ai ha^{-1} and 1000 g ai ha^{-1}.

The interaction between herbicide and application rate had a significant effect ($p<0.05$) on weedy rice density (Table 2). Oxadiazon and pretilachlor demonstrated complete suppression of weedy rice emergence when treated with 500 g ai ha^{-1}. By contrast, as the rate of pendimethalin increased, a corresponding decrease in weedy rice density was observed. For example, 250 g ai ha^{-1} pendimethalin led to reduction in weedy rice density by 37%. Increasing the herbicide rate to 500 and 1000 g ai ha^{-1} resulted in further reduction by 60% and 91%, respectively. The results obtained from this study underscore the importance of considering both the herbicide type and herbicide rate when attempting to control weedy rice. Oxadiazon and pretilachlor at 500 g ai ha^{-1} exhibited the strongest inhibitory effect on both density and dry weight compared to pendimethalin. In Bangladesh, single application of 250 g ai ha^{-1} pretilachlor or 500g ai ha^{-1} oxadiazon was also found to be effective in controlling weeds in wet-seeded rice (Shahabuddin et al. 2016). Furthermore, increasing the rate of pretilachlor to 900 g ai ha^{-1} was shown to effectively control weedy rice and improve the yield of cultivated rice (Shen et al. 2013). Pendimethalin at 1000 g ai ha^{-1} exhibited a significant level of weedy rice control similar to that observed with pretilachlor and oxadiazon at 500 g ai ha^{-1} (Table 2). However, pendimethalin was excluded from further experiments in this study due to reports of adverse effects on rice plants. Langaro et al. (2017) found that high rates of pendimethalin can cause a reduction in the photosynthetic rate and efficiency of carboxylation in rice plants. Additionally, Khaliq and Matloob (2012) reported increased seed mortality and reduced rice germination when pendimethalin was used at rates between 0.6 and 1.1 kg ai ha^{-1}.

TABLE 1. Main effect pre-emergent herbicides and application rates on the dry weight of weedy rice

Source	Dry weight (%)
Herbicide	
Oxadiazon	5 b
Pendimethalin	32a
Pretilachlor	8 b
Concentration (g ai ha^{-1})	
250	31 a
500	10 b
1000	5 b

Means within a column of each main effect followed by the same letter are not different according to the Tukey test at 5% significance. Data were expressed as percentages relative to their respective controls

TABLE 2. Interaction effect of pre-emergent herbicide and application rate on weedy rice density

Herbicide	Application rate (g ai ha^{-1})	Density (%)
Oxadiazon	250	27.0 b
	500	0 c
	1000	0 c
Pendimethalin	250	63 a
	500	40 b
	1000	9 c
Pretilachlor	250	34 b
	500	0 c
	1000	0 c

Means within a column of each main effect followed by the same letter are not different according to the Tukey test at 5% significance. Data were expressed as percentages relative to their respective controls

EFFECTS OF HERBICIDES AND SOIL WATER CONDITIONS ON WEEDY RICE

It is worth noting that there was a significant interaction ($p < 0.05$) between herbicide type and soil water condition on dry weight and density of weedy rice (Table 3). Under saturated soil water condition, oxadiazon reduced dry weight and density of weedy rice by 80 and 79%, respectively. Meanwhile, pretilachlor had a lower inhibition of weedy rice growth and density that ranged from 50 to 59%. Interestingly, when the soil was flooded, both herbicides provided complete inhibition of weedy rice. The findings highlight that the effectiveness of pretilachlor and oxadiazon is greatly influenced by the moisture levels in the soil. It is more likely, when pretilachlor or oxadiazon applied in saturated soil water condition, most of herbicide molecules are absorbed by soil colloids (Dilipkumar, Adzemi & Chuah 2012), thus resulting in less availability of herbicide for weedy rice uptake. However, under flooded conditions, adequate moisture in the soil could enhance the efficacy of pretilachlor and oxadiazon likely due to more free herbicide molecules available for weedy rice uptake. This finding aligns with the similar pattern observed by Lim et al. (2015), who suggests that the combination of flooding and pretilachlor application was more effective in suppressing weed emergence and biomass production compared to sole flooding or pretilachlor application alone. In another study by Dorji et al. (2013), it was reported that the combined utilization of pretilachlor and flooding demonstrated significant efficacy in inhibiting the germination and development of rice weeds such as, *Cyperus difformis*, *Ludwigia hyssopifolia*, and *Echinochloa colona*. On the other hand, Lin, Chen and Qiang (2016) demonstrated that pre-sowing application of oxadiazon at 450 g ai ha^{-1} under dry soil conditions inhibited weedy rice emergence by 44%, while the efficacy level was increased almost 2-fold (86%) when the same oxadiazon rate was applied under standing water conditions.

PHYTOTOXIC EFFECTS OF HERBICIDES ON CULTIVATED RICE UNDER DIFFERENT SOWING TIMES

There was no significant interaction ($p > 0.05$) between herbicide type and rice sowing time on dry weight and density of rice. The only factor exhibiting a significant effect ($p < 0.05$) was the main effect of rice sowing time. Pretilachlor and oxadiazon reduced rice density by 13-18% and dry weight by 22-28%. However, the phytotoxic effects observed in the glasshouse study are expected to be reduced under field conditions. The complex and diverse field ecosystem along with factors such as increased soil volume, microbial degradation, and herbicide runoff/leaching can contribute to the diminished impact of oxadiazon and pretilachlor on rice (Awan et al. 2016; Chauhan & Johnson 2011; Ryu, Jeong & Cho 2020). The present study has demonstrated the significant impact of rice seed sowing timing on the phytotoxic effects of pretilachlor and oxadiazon. When rice seeds were sown three days after herbicide treatment, the dry weight and density of rice were only 41% and 56% of the control, respectively, when averaged across herbicides. However, sowing the rice seeds at 6 and 12 days after herbicide treatment showed negligible phytotoxic effects on rice, with dry weight ranging from 90 to 95% and density from 96 to 100% compared to the control. The absence of phytotoxicity on rice seeded above 6 days after treatment was attributed to the lack of herbicide activity through the soil (Table 4). Similar results were reported by Estorninos Jr. et al. (2005), who demonstrated that oxadiazon could be safely applied 15 days before rice seeding for effective weedy rice control. Present study recommended delaying rice seed sowing for at least six days after applying pretilachlor or oxadiazon to mitigate the phytotoxic effects on rice. However, it should be noted that the specific conditions of the experiment, such as soil type and climatic factors, may influence the optimal sowing time and should be taken into consideration when implementing these findings.

TABLE 3. Interaction effect of pre-emergent herbicide and soil water condition on dry weight and density of weedy rice

Herbicide	Soil water condition	Dry weight (%)	Density (%)
Oxadiazon	Saturated	20 b	21 b
Oxadiazon	Flooded	0 c	0 c
Pretilachlor	Saturated	41 a	50. a
Pretilachlor	Flooded	0 c	0 c

Means within a column followed by the same letter are not different according to the Tukey test at 5% significance. Data were expressed as percentages relative to their respective controls

TABLE 4. Main effects of pre-emergent herbicide and rice sowing time on the dry weight and density of cultivated rice (MR297)

Source	Dry weight (%)	Density (%)
Herbicides		
Oxadiazon	72 a	82 a
Pretilachlor	78 a	87 a
Seed sowing time (day)		
3	41 b	56 b
6	90 a	96 a
12	95 a	100 a
Significant		
Herbicides (H)	0.2454	0.0565
Sowing time (S)	<.0001	<.0001
H*S	0.1096	0.1170

Means within a column of each main effect followed by the same letter are not different according to the Tukey test at 5% significance. Data were expressed as percentages relative to their respective controls

Conclusions

This study has demonstrated that effective control of weedy rice can be achieved through the proper application of pre-emergent herbicides. The results have shown the potential of pretilachlor and oxadiazon applied under standing water conditions, with the water level being maintained for a period of 7 days to eliminate weedy rice seeds in the soil without injuring rice plants. This finding holds significant implications for direct-seeded rice fields during land preparation. By incorporating the proposed approach into the cultivation process, pretilachlor or oxadiazon can be sprayed under standing water after the final tillage and prior to land leveling. Subsequently, on the 7th day, the water can be flushed out, and the land can be leveled to facilitate the broadcasting of rice seeds. To further validate the effectiveness of this new approach, additional field studies are essential. Conducting field trials will provide empirical data and insights into the performance and sustainability of this weedy rice control in direct-seeded rice system.

ACKNOWLEDGEMENTS

Financial support was provided by the Ministry of Agriculture and Agro-Based Industry, Malaysia – MARDI (P-RI501-0903). No conflicts of interest have been declared.

REFERENCES

Ahmed, S., Salim, M. & Chauhan, B.S. 2014. Effect of weed management and seed rate on crop growth under direct dry seeded rice systems in Bangladesh. *PLoS ONE* 9(7): E101919. http://Dx.Doi.Org/ 10.1371/Journal. Pone.00101919

Awan, T.H., Sta Cruz, P.C. & Chauhan, B.S. 2016. Effect of pre-emergence herbicides and timing of soil saturation on the control of six major rice weeds and their phytotoxic effects on rice seedlings. *Crop Protection* 83: 37-47.

Chaudhary, A., Venkatramanan, V., Kumar Mishra, A. & Sharma, S. 2022. Agronomic and environmental determinants of direct seeded rice in South Asia. *Circular Economy and Sustainability* 3: 253-290.

Chauhan, B.S. & Johnson, D. 2011. Growth response of direct-seeded rice to oxadiazon and bispyribac-sodium in aerobic and saturated soils. *Weed Science* 59(1): 119-122.

Dilipkumar, M., Adzemi, M. & Chuah, T. 2012. Effects of soil types on phytotoxic activity of pretilachlor in combination with sunflower leaf extracts on Barnyardgrass (*Echinochloa crus-galli*). *Weed Science* 60(1): 126-132.

Dilipkumar, M., Kumar, V., Song, B., Olsen, K.M., Chuah, T., Ahmed, S. & Qiang, S. 2021. Weedy rice (*Oryza* spp.). In *Biology and Management of Problematic Crop Weed Species,* edited by Chauhan, B.S. Massachusetts: Academic Press. pp. 285-309.

Dorji, S., Chauhan, B.S., Baltazar, A.M. & Johnson, D.E. 2013. Effect of flooding depth and pretilachlor rate on emergence and growth of the rice weeds: Junglerice (*Echinochloa colona*), smallflower umbrella sedge (*Cyperus difformis*), and ludwigia (*Ludwigia hyssopifolia*). *Canadian Journal of Plant Protection* 1: 43-48.

Estorninos Jr., L.E., Gealy, D.R., Talbert, R.E. & Gbur, E.E. 2005. Rice and red rice interference. I. Response of red rice (*Oryza sativa*) to sowing rates of tropical japonica and indica rice cultivars. *Weed Science* 53: 676-682.

Karim, R.S.M., Man, A.B. & Sahid, I.B. 2004. Weed problems and their management in rice fields of Malaysia: An overview. *Weed Biology Management* 4: 177-186.

Khaliq, A. & Matloob, A. 2012. Germination and growth response of rice and weeds to herbicides under aerobic conditions. *International Journal of Agriculture and Biology* 14: 775-780.

Kumar, V. & Ladha, J.K. 2011. Direct seeding of rice: Recent developments and future research needs. *Advances in Agronomy* 111: 297-413.

Langaro, A.C., Agostinetto, D., Ruchel, Q., Garcia, J.R. & Perboni, L.T. 2017. Oxidative stress caused by the use of preemergent herbicides in rice crops. *Revista Ciencia Agronomica* 48: 358-364.

Li, L., Li, Y., Jia, Y., Caicedo, A.L. & Olsen, K.M. 2017. Signatures of adaptation in the weedy rice genome. *Nature Genetics* 49: 811-814.

Lim, C.A.A., Awan, T.H., Sta. Cruz, P.C. & Chauhan, B.S. 2015. Influence of environmental factors, cultural practices, and herbicide application on seed germination and emergence ecology of *Ischaemum rugosum Salisb*. *PLoS ONE* 10(9): E0137256. http://Dx.Doi.Org/10.1371/Journal. Pone.000137256

Lin, Y., Chen, H. & Qiang, S. 2016. A technique for oxadiazon application in controlling weedy rice in direct-seeded rice fields. *Acta Phytophylacica Sinica* 43: 1033-1040.

Olajumoke, B., Juraimi, A.S., Uddin, M.K., Husni, M.H. & Alam, M.A. 2016. Competitive ability of cultivated rice against weedy rice biotypes: A review. *Chilean Journal of Agricultural Research* 76: 242-251.

Ryu, J.H., Jeong, H. & Cho, J. 2020. Performances of vegetation indices on paddy rice at elevated air temperature, heat stress, and herbicide damage. *Remote Sensing* 12(16): 2654. https://doi.org/10.3390/rs12162654

Samal, P., Babu, S.C., Mondal, B. & Mishra, S.N. 2022. The global rice agriculture towards 2050: An inter-continental perspective. *Outlook on Agriculture* 51(2): 164-172.

Shahabuddin, M., Hossain, M.M., Salim, M. & Begum, M. 2016. Efficacy of pretilachlor and oxadiazon on weed control and yield performance of transplant *Aman* rice. *Progressive Agriculture* 27(2): 119-127.

Shen, X., Gao, X., Eneji, A.E. & Chen, Y. 2013. Chemical control of weedy rice in precise hill-direct-seeded rice in South China. *Weed Biology and Management* 13: 39-43.

Singh, Y., Singh, V.P., Singh, G., Yadav, D.S., Sinha, R.K.P., Johnson, D.E. & Mortimer, A.M. 2011. The implications of land preparation, crop establishment method and weed management on rice yield variation in the rice-wheat system in the Indo-Gangetic plains. *Field Crop Research* 121: 64-74.

Su, X., Zhan, J.J., Wang, J.Q., Li, X.M., Wei, Y.H., Wu, H. & Dai, H.F. 2022. Development status of direct seeding rice and study on response mechanism of submergence. *Open Access Library Journal* 9: e8613.

Tseng, T.M., Burgos, N.R., Shivrain, V.K., Alcober, E.A. & Mauromoustakos, A. 2013. Inter- and intrapopulation variation in dormancy of *Oryza sativa* (weedy red rice) and allelic variation in dormancy-linked loci. *Weed Research* 53(6): 440-451.

Ziska, L.H., Gealy, D.R., Burgos, N., Caicedo, A.L., Gressel, J., Lawton-Rauh, A.L., Avila, L.A., Theisen, G., Norsworthy, J., Ferrero, A., Vidotto, F., Johnson, D.E., Ferreira, F.G., Marchesan, E., Menezes, V., Cohn, M.A., Linscombe, S., Carmona, L., Tang, R. & Merotto Jr., A. 2015. Weedy (red) rice: An emerging constraint to global rice production. *Advances in Agronomy* 129: 181-228.

*Corresponding author; email: dilip@mardi.gov.my