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Review Article

Managing weedy rice (*Oryza sativa* L.) in Malaysia: challenges and ways forward

Muhamad Shakirin Mispan[a,b,*], Mahyoub Izzat Bzoor[a], Intan Filzah Mahmod[a], Abdul Hayyan Basit Md-Akhir[a], Amalia Qistina Zulrushdi[a]

a Institute of Biological Sciences, Faculty of Science, University of Malaya, 50603, Kuala Lumpur, Malaysia.

b Centre for Research in Biotechnology for Agriculture (CEBAR), University of Malaya, 50603, Kuala Lumpur, Malaysia.

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ABSTRACT

Rice industry in Malaysia faces serious challenges in managing weedy rice (*Oryza sativa* L.) since it was first observed in 1988. Unfortunately, there is no simple control method for weedy rice. Recommended practices in Malaysia adopted various integrated weedy rice management strategies mainly on land preparation and pre-harvest period controls. Multiple tillage, chemical applications via pre-emergence and pre-sowing herbicide, and manual weeding are the usual weedy rice control practices by majority of Malaysian farmers. The conspecific nature of weedy rice with cultivated rice increased the difficulty to control the weed with several weedy rice biotypes have already mimic the local varieties. Introduction of Clearfield® Rice Production System (CPS) in 2010 has shifted the current weedy rice management strategies to an herbicide-tolerant crop approach. Some concerns of the technology including potential resistant to weedy rice and environmental issues were discussed. Additional weedy rice management strategies as alternative approaches for Malaysia rice agro-ecosystems were proposed in this review to fill the gaps on current weedy rice controls including reducing cross contamination between farms, managing weedy rice seedbank, empowering alternative culture methods in rice farming, strengthening current Clearfield® system, and exploring 'omics' research for other potential herbicide tolerant rice. Improvement in communication is proposed to ensure any information on weedy rice management is effectively transferred between farmers and authorities.

Introduction

Weedy rice (*Oryza sativa* L.) has become one of the notorious weeds in rice agro-ecosystems all over the world (Baki, 2006; 2010). Weedy rice infestation became apparent over the last 35 years

Corresponding author, email: shakirin@um.edu.my (Muhamad Shakirin Mispan).

mainly after the introduction of direct seeding technique and the cultivation of weak, semi-dwarf *indica*- type varieties (Ferrero, 2003; Delouche et al. 2007). The emergence and fast spread of weedy rice were also resulted from poor land preparation which increased the survival fate of weedy rice (Figure 1) in the seedbank (Azmi and Karim, 2008; Chauhan, 2013). In Malaysia, weedy rice was first reported in 1988 in Sekinchan, Selangor (Wahab and Suhaimi, 1991). Since then, the infestation was fast spread to other rice granaries in Peninsular Malaysia including Seberang Perak and Kerian-Sg. Manik, Perak; Ketara, Terengganu; and MADA, Kedah (Baki et al. 2000; Baki, 2004; Azmi et al. 2005a; Anuar et al. 2014) with wide phenotypic variations (Baki, 2004; Sudianto et al. 2016). Entering the millennium, more than 50 per cent of rice granaries in Tanjung Karang, Selangor and Besut, Terengganu were reported to be infested with weedy rice (Azmi et al. 2000; Anuar et al. 2014), while in Muda, Kedah weedy rice was dominant with registered infestation level ranging from less than 10 per cent to more than 20 per cent coverage (Azmi et al. 2005a,b).

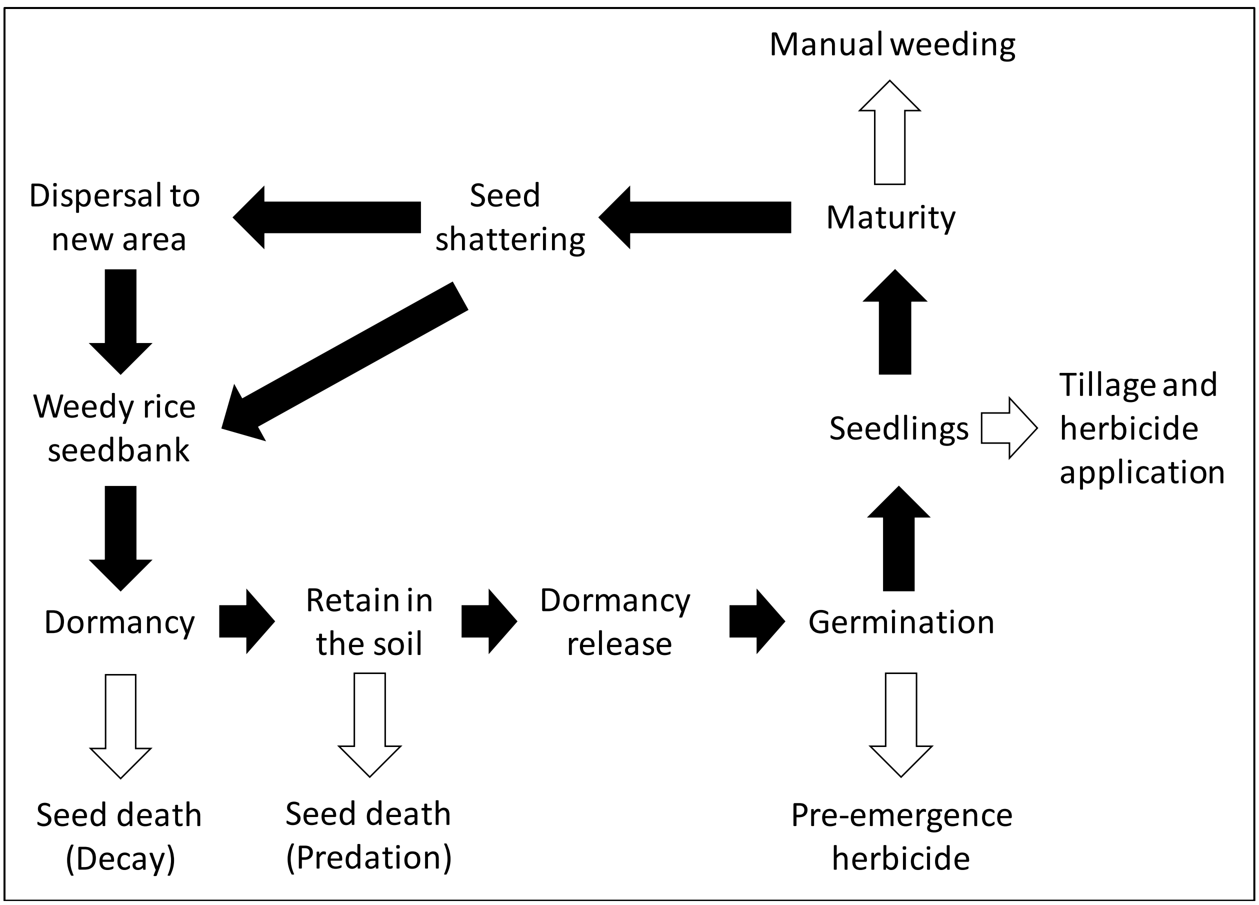

Figure 1. Weedy rice fate in rice agro-ecosystems. The weed survival cycle to escape for successive seasons is presented by black arrows. Weedy rice can be "withdrawn" from the field by natural and human activities as indicated with white arrows.

The infestation was also temporally dynamic in recent years especially in states of Kedah, Perak and Selangor (Baki and Shakirin, 2010). The weedy rice infestation was not significant in 1995 but it was skyrocketed in 1996 with more than 19,900 ha of rice farms were infested in Peninsular Malaysia (Baki et al. 2000; Azmi et al. 2005b). In 2001, it was reported that weedy rice was found in 82 per cent of Muda rice fields but reduced to only 59 per cent fields having at least a 10 per cent infestation rate in 2002. However, the infestation tremendously increased in 2005 where 91 per cent of rice fields were infested, with 88 per cent accounted of at least 10 per cent infestation (Baki et al. 2000; Baki, 2006). Spatial distribution pattern of weedy rice in Malaysia generally showed a uniform but restricted distribution with recorded variance-to-mean ratio and Lloyd's patchiness index values less than one (Baki et al. 2000; Baki and Shakirin, 2010). Infestation of weedy rice caused severe rice production loss due to the competitive nature of weedy rice against cultivated rice (Diarra et al. 1985; Delouche et al. 2007; Chauhan, 2013). It was reported that the national rice yield loss can be projected to 64,880 tons by only 5 per cent weedy rice infestation (Baki, 2004) and can lead to monitory loss exceeding $20 million (Anuar et al. 2014). There is no simple control method for weedy rice (Delouche et al. 2007). The close morphological similarity between weedy rice and other commercial rice varieties (Song et al. 2014; Sudianto et al. 2016) has "vetoed" any herbicide applications that selectively control other rice weed species (Sudianto et al. 2016), making weedy rice close to impossible to be controlled and managed chemically (Mispan et al. 2015). In Asia, the common weedy rice management strategies incorporate preventive measures, land preparation, rice establishment methods, seeding rate, weed-competitive cultivars, water management, herbicide application and crop rotation (Chauhan, 2013).

Weedy rice management practices in Malaysia and its challenges

The implementation of direct seeding practice as a shift from laborious transplanting was a spark of weedy rice infestation in most rice granaries and farms in Malaysia (Azmi et al. 2000; Baki and Shakirin, 2010). The integrated approach (Table 1) includes straw burning, shallow tillage, pre-emergence herbicide application, multiple tillage (dry and wet), sowing of pre-germinated seeds, flooding, ditches/levees control, hand-weeding, panicle roguing and weed-free crop (Azmi and Abdullah, 1998; Azmi et al. 2000; Azmi and Karim, 2008).

Table 1. Management practices recommended for weedy rice control*.

Time	Activity	Remark
After Harvest		
1-3d after harvest	Cut stubble	Service cutter or shredder attached to a 4-wheel tractor. The straw and stubble are spread evenly.
3-7d after harvest	Straw burning	To destroy weedy rice seed and to promote new emergence from the seedbank
Pre-planting		
33d before sowing	First herbicide application	Glyphosate; Glufosinate
30d before sowing	Dry rototilling/shallow tillage (1st tillage)	Shallow rotovation up to 7.5cm. Removal of perennial weeds and to encourage weedy rice seeds emergence.
15d before sowing	Wet rototilling (2nd tillage)	To encourage weedy rice emergence.
10d before sowing	Second herbicide application	Glyphosat; Glufosinate; Pretilachlor
2d before sowing	Wet rototilling and land levelling	Removed emerged weedy rice. Water level at 3cm distribution is used as a standard reference for land levelling.
Sowing day		
0d	Pre-germinated rice seed broadcasting	Sowing immediately after land levelling.
0-3d after sowing	Pre-emergence herbicide application	Pretilachlor; Benthiocarb/propanil; Pretilachlor/Propanil.
7-14d after sowing	Flooding	
>20d after sowing	Weedy rice monitoring and manual weeding	Cutting off panicles of weedy rice to reduce future seedbank.
Harvest		
110-120 d after sowing	Harvesting	Combined harvester should be cleaned properly especially from highly infested areas to avoid the spread of weedy rice seed.

* Adapted and modified from Azmi and Muhammad (2003) and Azmi and Karim (2008).

Weedy rice conspecific nature with commercial rice varieties has made it difficult to use herbicide as chemical control (Mispan et al. 2013). Pre-emergence and pre-sowing herbicides application are the most common practices for chemical application to manage the emergence of weedy rice and other rice weeds in Malaysia rice agro-ecosystems (Baki, 2004). Some commonly used herbicides in the Malaysian rice cultivation system to control weedy rice are shown in Table 2 (Baki, 2004, Azmi and Karim, 2008; Saad et al. 2017). Despite the high efficiency of herbicide to control most rice weeds, there were no selective herbicide to control weedy rice during the post emergence stages until the introduction of Clearfield® Rice Production System (CPS) in 2010.

Table 2. List of commonly used herbicides for weedy rice management in Malaysia *.

Common name	Trade name	Notes
MCPA	Many trade names	Controls weedy rice (general weed control) on bunds, levees, drains and irrigation canals.
Pretilachor	Sofit	Pre-emergence (0.5 kg a.i./ha)
Benthiocarb	Bolero	Pre or early post emergence (3.4-4.5 kg a.i./ha) at 4-10 days after seeded. Maintain flooding 3-5d after treatment but not submerging the rice plants.
Fluazfop_P	Fusilade	Pre-emergence before tillage at 2-4 leaf stages of weedy rice. Oil adjuvant or anionic surfactant is required.
Glyphosate	Roundup	Pre-emergence prior to tillage or zero tillage in transplanted- or dry or water-seeded rice.
Molinate	Ordram	Pre-planting incorporated in water seeded rice (3 kg a.i./ha).
Propanil	Tawan	Post-emergence (2-4 kg a.i./ha)
Quinclorac	Rumpas M	Post-emergence (0.25 kg a.i./ha)

*Adapted from Baki (2004), Azmi and Karim (2008), and Saad et al. 2017.

In the early 90's to middle 2000's, most farmers practiced hand-weeding in their direct-seeded farm by roguing the weedy rice (Azmi and Karim, 2008). Since the weed was generally taller in stature than cultivated varieties, farmers can easily identify them and slashing the weedy rice panicles before harvest (Baki, 2010; Baki and Shakirin, 2010). Selective weeding was effectively controlling weedy rice infestation during this period especially in the Sekinchan area, but this practice was found impractical especially in broadcast-seeded rice (Azmi and Karim, 2008), resulting in accidental damage of cultivated rice during the process. High labor costing also caused many farmers to abandon their farms if the weedy rice infestation was extreme (Kadir and Kamariah, 2003; Mispan et al. 2015). To make it worse, the recent report on the emergence of new biotypes of weedy rice (NBWRs) which morphologically mimics commercial cultivated varieties (*i.e.* MR220 and MR219) especially in height, making weedy rice almost unrecognizable (Mispan, 2008, Baki and Shakirin, 2010; Mispan et al. 2015) and caused hand-weeding impossible. Although the NBWRs infestation was still in the early stages, their distribution pattern was found to be like the previously weedy rice emergence in Malaysia (Baki and Shakirin, 2010). If there is no serious immediate action taken, the infestation of these new biotypes and weedy rice in general, can be severe in the country. Weedy rice can be effectively controlled during the pre-planting stage (Azmi and Karim, 2008; Chauhan, 2013). Managing the weedy rice seedbanks size with proper land preparation can minimize the severity of the infestation. Sequential tillage operations during land preparation and pre-planting management practices have reduced weedy rice seedbanks in most rice granaries in Malaysia especially in direct-seeded farms (Azmi et al. 2000; Chauhan, 2013). Weedy rice is known to have longer seed longevity (Suh, 2008; Noldin et al. 2006), higher venerability in soil (Vaughan, 1994), and can stay dormant longer (Chang, 1991; Moldenhauer and Gibbons, 2003; Ye et al. 2015) than cultivated rice. Maintaining viability over longer period might provide several adaptive advantages for weedy rice to survive from heat and high humidity and escape seed deterioration especially in tropical areas (Roberts, 1961; McDonald, 1999; Baek and Chung, 2012). Theoretically, moving seeds from a soil surface to the deep soil could help maintain weedy rice seed dormancy or induce its secondary dormancy, resulting in enhanced seed longevity. In contrast, moving buried viable seeds to the topmost soil or surface could promote dormancy release and germination (Benvenutti et al. 2001; Noldin et al. 2006; Fogliatto et al. 2010; Roham et al. 2014; Bhullar and Chauhan, 2015).

Albeit the proposed land preparation strategies have shown efficacy to control weedy rice, the weed continues to prevail (Azmi et al. 2003; Baki, 2010; Azmi et al. 2012). This is mainly due to the failure of most farmers to follow the proposed standard operating procedures for land preparations because of high investment for cost and time (Kadir and Kamariah, 2003; Azmi and Karim, 2008). The movement of seeds by tillage into the seedbank (Ashrafi et al. 2003; Konstantinovic et al. 2011; Roham et al. 2014) might also contribute to weedy rice perseverance in the soil (Baek and Chung, 2012). At conventionally tilled farms, weed seeds can be buried up to 5 cm to 10 cm below the soil surface (Bhullar and Chauhan, 2015). The switch from direct seeding method to manual transplanting method using a transplanter has helped farmers reducing weedy rice infestation *via* seed contamination (Azmi et al. 2005b). Seed contamination in Malaysia's rice production generally caused by weed-contaminated rice seeds and weedy rice seeds movement from single-usage harvesters to multiple rice fields (Kadir and Kamariah, 2003). Azmi et al. (2005a) reported certified seeds from direct seeding culture may already contaminated with weedy rice seeds where weedy rice panicles ranged from 0.48-3.05 panicles/m^2 were found in direct seeded crops from ten licensed producers. Therefore, the mechanical transplanting was proven to tremendously reduce weedy rice infestation in Malaysia and can increase rice yield from 4.01 tonne/ha to 7.1 tonne/ha as in a plot trial in Selangor (Azmi et al. 2005a). Other crop establishment methods were also recommended to Malaysian farmers including water seeding (Azmi et al. 2001; Azmi and Muhamad, 2003) and seedling broadcasting (Azmi and Karim, 2008; Chauhan, 2013). Water seeding decreased weedy rice effect by 20 per cent and reduced it return by 70-76 per cent (Azmi et al. 2001; Azmi and Muhamad, 2003), while seedling broadcasting was reported to be more effective in reducing weedy rice than water seeding and manual transplanting (Azmi and Johnson, 2006; Juraimi et al. 2013). However, the application of these techniques is still limited and not too popular (Azmi and Karim, 2008; Juraimi et al. 2013).

Clearfield® Rice Production System (CPS): an approach to control weedy rice via herbicide tolerant crop in Malaysia

Herbicide-tolerant rice cultivars have been proposed to Malaysian farmers to be the current best solution to combat weedy rice especially in direct-seeding system (Azmi et al. 2012; Sudianto et al. 2013). Clearfield® Rice Production System (CPS) was introduced in Malaysia in 2010 with two varieties, *i.e.* MR220-CL1 and MR220-CL2. These imidazolinone tolerant rice (IMI-TR) varieties were developed by crossing United States IMI-TR Line No. 1770 with local cultivar, MR220, using conventional breeding technique (Azmi et al. 2012). This system uses imidazolinone (IMI) herbicides (Malaysia commercial name: OnDuty®) which is a selective herbicide that inhibits the ALS enzyme and the three-amino acid branched chains: isoleucine, leucine, and valine. It stops protein synthesis, and eventually kills any susceptible plants (weeds) including weedy rice (Azmi et al. 2012; Sudianto et al. 2013).

Introduction of CPS as a pilot study in Seberang Perak rice granaries has become popular to other rice growing states (*i.e.* Selangor and Kedah) because of the success of this system to control many grass weed species including weedy rice while boosting rice production (Sudianto et al. 2013). This system increased yield production by 5 to 8 times (Azmi et al. 2012). Recent report by Department of Agriculture (Department of Agriculture, 2016) indicates that Clearfield® variety MR220-CL2 (56.9 per cent) is the most frequent rice variety planted in Peninsular Malaysia followed by MR263 (17.9 per cent), and MR219 (8.3 per cent indicating the farmers acceptance to CPS. The report also stated that both CPS varieties produced the highest average yield among other most popular varieties with the highest yield reached 9.7 tons/ha. Despite the current popularity and successes in yield improvement and weedy rice control of CPS in most major rice granaries in Malaysia, Sudianto et al. (2013) has listed four major challenges for this system to become sustainable in Malaysia: 1) IMI-resistant weedy rice evolution; 2) volunteer Clearfield® rice; 3) seed system; and 4) IMI herbicides carryover effect. One of the major concerns of CPS is the probability of weedy rice to become resistant to OnDuty®. Will weedy rice turns into a '*super-weed*' or what local farmers call *kebal* (invulnerable). Historically, continuous use of phenoxy herbicides from the late 1980s has resulted in a shift of weed species in Malaysia rice granaries in favour of such graminaceous species including barnyard grass (*Echinochloa crus-galli* (L.) Beauv.), jungle rice

(*E. colona* (L.) Link.), red sprangletop (*Leptochloa chinensis* (L.) Nees.), saramollagrass (*Ischaemum rugosum*), knotgrass (*Paspalum distichum* L.), and eventually of late, the weedy rice (Baki, 2004, 2007). Despite various reports of gene flow and IMI-tolerance weedy rice in the world (Table 3), up-to-date, there is still no solid reports on weedy rice resistant status in Malaysia although CPS was already introduced for more than five years since 2010.

Table 3. The occurrence of gene flow of Clearfield® rice to weedy rice in commercial rice fields *.

Location	Clearfield® rice variety	Variety release (year)	Reported resistant (year)	Percentage of gene flow (average)
Louisiana, US.	CL121, CL141, CL161	2001/2002	2002	0.17%
Arkansas, US.	CL161	2002	2003	0.11%-0.76%
Brazil	IRGA 422 CL	2003	2004/2005	0.065%
Colombia	CF205	2003	2006	<1%
Costa Rica	CFX-18/CL161	2004	2007	Not available
Italy	Libero	2006	2010	Not available

*Adapted from Sudianto et al. (2013)

A preliminary study at three townships in Kedah as presented by a group from University Putra Malaysia in the 25th Asian-Pacific Weed Science Society Conference that there is high likely that weedy rice has developed resistance to IMI-herbicide at various level based on the weedy rice escapes in CPS rice fields in these areas (Jaafar et al. 2014). Weedy rice in Malaysia also reported to have the capability to hybridize with Clearfield® rice when grown together (Engku et al. 2016). With the continued usage of CPS and its increase popularity among farmers, the Malaysian rice agro-ecosystem may face ecological risks of weedy rice 'evolution' if there are no thorough studies, screenings and stringent ecological risk assessments of imidazolinone-resistant weedy rice. Herbicide carryover from the implementation of CPS is another major concern and challenge (Bajrai et al. 2017; Mahyoub et al. 2017; Bzour et al. 2018). The carryover of imidazolinone was reported to affect many non-rice crops in rotational systems (Allister and Kogan, 2005; Bahm et al. 2011). Imidazolinone residues in the soil were already detected in Malaysia rice field (Bajrai et al. 2017; Mahyoub et al. 2017) which could potentially impact non-IMI rice cultivars in CPS rotation system (Bzour et al. 2018). Proper and organized studies, researches and surveys of imidazolinone carryover in CPS rice fields in Malaysia need to be orchestrated by various organizations and institutions to reduce the herbicidal impact to human and environment (Bzour et al. 2018). Personal communications with local farmers in IADA Barat Laut Selangor rice granary indicates that the residue from CPS farms has already caused damages to their side farming (*e.g.* corn, tapioca, and banana), poultry and livestock. These stated challenges on CPS application need to be addressed and taken seriously by all related parties in Malaysia. Long-term planning, appropriate stewardship, research intensity, government support and strong collaboration among Malaysian institutions need to be aligned for the sustainable lifespan of this technology in Malaysia (Sudianto et al. 2013; Mispan et al. 2015).

Alternative approaches for weedy rice management strategies in Malaysia

Weedy rice management in Malaysia is basically concentrating on proper land preparation during pre-planting stage (Azmi and Karim, 2008) and by herbicide tolerant crop (HTC) *via* Clearfield® Production System (CPS) as previously discussed. Based on the weedy rice life cycle model (Figure 2) proposed by Pandey et al. (2000), weedy rice is principally controlled by: 1) managing seedbank by rice straw burning, 2) early weedy rice elimination by proper pre-planting land preparation and herbicide (CPS) application, and 3) manual weeding (Figure 2).

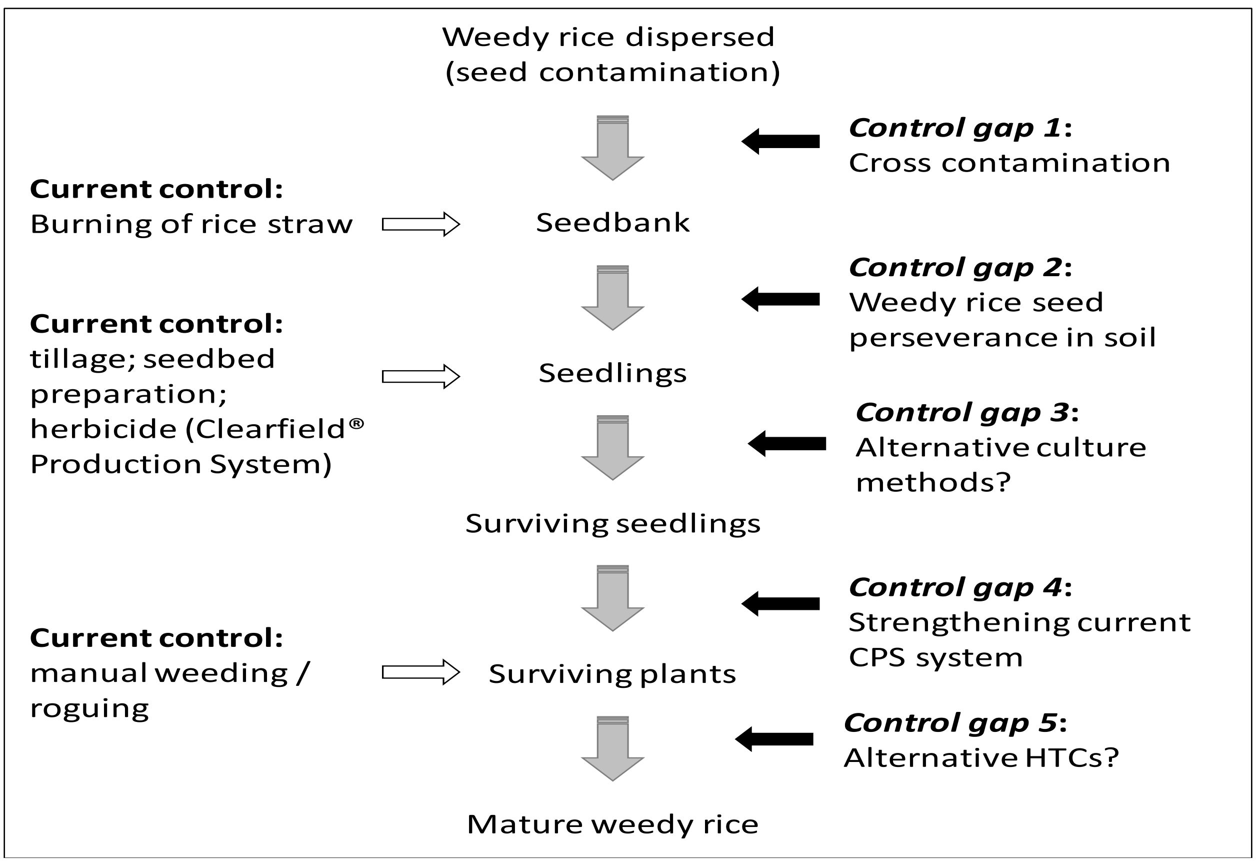

Figure 2. Current controls (white arrow) and potential control gaps (black arrows) for weedy rice management based on the weedy rice life cycle model from Pandey et al. (2000).

This leaves a few gaps especially between stages of weedy rice development. Manipulation of this life cycle can quantify the outcome of various strategies in the weedy rice management strategies by concentrating on reducing; 1) weedy rice seedling survival; 2) weedy rice vegetative survival; 3) weedy rice seed rain; and 4) seed contamination through seed import (Azmi and Karim, 2008, Baki, 2010). The challenge is to add more controls to fill the gaps which can become the potential for weedy rice escape to the rice agro-ecosystem (Figure 2). For '*Control Gap 1*', inter-farm weedy rice cross contamination needs to be reduced by imposing intensive regulatory measures to the rice growers in Malaysia. The movement of machineries (*e.g*. plowers, harvesters) from one field to another need to be limited or thoroughly cleaned from any weed seeds. This can reduce the spread of weedy rice seeds especially when the harvester moves from highly infested field. The use of certified seeds by farmers need to be strictly regulated considering the major entry point of weedy rice is by contaminated seeds. Re-use of seeds from previous season and sharing seeds need to be prohibited. The government or any authorities need to find a way to impose of using only certified seeds by a competent body/s to reduce the possibility of seed contamination.

Maintaining viability over longer period of time in the seedbank might provide several adaptive advantages for weedy rice to survive (Roberts, 1961; McDonald, 1999; Baek and Chung, 2012). The persistence of weedy rice to deterioration of aging seed in nature especially by strong dormancy is a common trait (Noldin et al. 2006; Gu et al. 2006). Despite being exposed to relatively high temperature and moisture that would usually enhance seed germination and deterioration, the weedy rice problem is still severe (Baek and Chung, 2012) especially in the tropics. Physiological mechanism of seed deterioration in rice has been well studied but the knowledge of the inheritance and genetic determinants of seed longevity mechanism in weedy rice are still lacking (Miura et al. 2002; Sasaki et al. 2005; Shigemune et al. 2008), or not as advanced as studies on seed dormancy (Gu et al. 2003; 2005; 2006). Therefore, in '*Control Gap 2'*, weedy rice seed longevity and durability study in the seedbank need to be emphasized and strategized to reduce or ultimately eliminate the possible escape. Preliminary study in two rice fields in Malaysia showed that weedy rice under poor land preparation has higher germinability of weedy rice seeds under various depths compared to a properly managed land (*unpublished data*). Weedy rice emergence is highly corresponding with direct-seeding rice culture (Baki and Shakirin, 2010; Sudianto et al. 2013; 2016). However, direct-seeded method is still popular in many rice granaries in Malaysia (Azmi et al. 2012; Department of Agriculture, 2016) due to low labour intensity and economical values (Dilipkumar et al. 2017). Chauhan (2013) and Abraham and Jose (2014) have proposed various cultural methods/strategies to manage weedy rice in the Asia-Pacific region. While not every method is suitable in Malaysian ecosystem, proposed approaches for '*Control Gap 3'* are focusing on diversifying the integrated strategies to manage weedy rice. The integrated weed management (IWM) concept is not new to the rice industry in Malaysia (Dilipkumar et al. 2017), but the acceptance level for new innovation and technology is significantly low among farmers (Mohamed et al. 2016; Nordin et al. 2017) - the challenge that need to be addressed.

Various crop establishment methods have already been tested in Malaysia and were proven to reduce weedy rice infestation (Azmi and Karim 2008; Chauhan 2013). Seeding pre-germinated rice seeds in water seeding method has lessen the effect of weedy rice by 20% and reduced the weed return to the soil by 70-76 per cent (Azmi et al. 2001; Azmi and Muhamad, 2003). Implementation of seedling broadcasting in rice fields by raising rice seedlings in holes of plastic sheets before random broadcasting was found to effectively reducing weedy rice infestation compared to water seeding and manual transplanting (Azmi and Johnson, 2006; Juraimi et al. 2013). Other IWM strategies which has already been studied in Malaysia include stale seedbed technique (Azmi and Karim, 2008; Juraimi et al. 2013); using high quality and weed-free seeds from certified source (Dilipkumar et al. 2017); herbicide rotation (Anwar et al. 2012); and high rice seeding (Azmi and Johnson, 2006). Diversifying these methods over some period of times may reduce the impact of weedy rice to become adapted or resistant from a single control method.

'Control Gap 4' and '*Control Gap 5'* are aimed to reduce the probability of weedy rice to become resistant to any herbicide applications and/or cultural methods. Understanding weedy rice adaptation to escape various management practices especially to chemical control is important and need a special focus (Sudianto et al. 2013; Jaafar et al. 2014; Mispan et al. 2015). The status of weedy rice resistant especially to CPS need to be clarified and mitigation strategies need to be immediately set up to reduce greater damage due to the resistance (Jaafar et al. 2014; Mispan et al.2015; Engku et al. 2016). Criticism has spread among farmers regarding the failure of IMI herbicides in effectively controlling weedy rice (Dilipkumar et al. 2017). Regrettably, farmers ignorance to follow CPS stewardship guidelines has caused this system failed to fully control weedy rice. This includes planting over two consecutive seasons, using uncertified CPS seeds, planting Clearfield® rice without OnDuty® treatment, inappropriate OnDuty® application timing, and applying OnDuty® at reduced dosage (Dilipkumar et al. 2017, Bzour et al. 2018). Therefore, in '*Control Gap 4'*, strengthening the enactment and enforcement of seed laws is required to prevent weedy rice escape *via* seed contamination. In addition, strict administration among farmers in following CPS stewardship guidelines is crucial to ensure the success of CPS or any other future HTC technologies in Malaysia.

Relying to only single HTC technology might increase the potential escape of weedy rice from herbicide treatment/s. Exploring 'omics' research in weedy rice to be integrated in weed management and plant breeding is something to ponder for '*Control Gap* 5' as an approach to broaden the application horizons of HTCs. The interest on genomics studies in weedy rice may arise in the country due to their rapid evolution dynamics in Malaysian rice agro-ecosystem (Mispan et al. 2015). Weedy rice also can become a model plant for weed ecological genetic studies to elucidate genetic and evolutionary mechanism of weed adaptation and competitiveness in agro-ecosystems using combinative approaches of ecology, genetics and genomics to provide fundamental knowledge to improve or devise new weedy rice management strategies (Mispan et al. 2013; Mispan, 2014). The biotechnology techniques and technologies especially in the metabolomics studies to illuminate useful chemical compounds (Saiman, 2014) can be transferred to weedy rice systems for further understanding on herbicide mechanisms and actions to weedy rice (Ruzmi et al. 2017). In addition to physical approaches (*Control Gaps 1-5*) to reduce the impact of weedy rice in rice production, education and awareness about weedy rice management need to be empowered. Technical support and outreach educational activities regarding the control and management of weedy rice for local farmers need to be strengthened. Regular awareness to local farmers on good agriculture practices through campaigns, lectures, field days and trainings will help the rice growers collectively in combating weedy rice infestation. Department of Agriculture, academic institutions, Malaysian Agricultural Research and Development Institute (MARDI) and other local or international organizations need to work hand in hand in supporting and providing adequate information to rice growers on weedy rice management.

Rice growers in Malaysia are mainly independent farmers with various size of land ownership. Therefore, the planting practices are generally varying between growers. The risk become greater when certain small farmers neglecting on practicing appropriate field management due to high cost and intensive labour. This may lead to patchiness of weedy rice infestation and high potential spread to neighbouring fields who follows best agriculture practices. Nordin et al. (2015) recommended communication improvement between farmers and the authorities to increase acceptance and understanding of farmers to any new rice farming innovations. Farmers' society/union especially through Farmers Organization Authority (LPP) and government institutions such as MUDA Agricultural Development Authority (MADA), KEMUBU Agricultural Development Authority (KADA), and Integrated Agricultural Development Projects (IADA) can be formed to synchronize the 'top-down' and 'down-top' communication for managing weedy rice.

Regulations can also easily impose when the rice growers understand the essence on any weed management strategies and technologies (Nordin *et al.* 2014; 2015; 2017).

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Conflict of Interest

Authors declare no conflict of interest.

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