Crop Protection xxx (2017) 1–9

Contents lists available at ScienceDirect

Crop Protection

journal homepage: www.elsevier.com/locate/cropro

Weed management issues, challenges, and opportunities in Malaysia

Masilamany Dilipkumar [a, *], Tse Seng Chuah [b], Sou Sheng Goh [c], Ismail Sahid [d]

[a] Inbred Rice Program, Rice Research Centre, Malaysian Agricultural Research and Development Institute (MARDI), MARDI Seberang Perai, 13200 Kepala Batas, Pulau Pinang, Malaysia
[b] School of Food Science and Technology, Universiti Malaysia Terengganu, 21030 Kuala Terengganu, Terengganu, Malaysia
[c] The RRIM Research Station, Malaysian Rubber Board, 47000 Sungai Buloh, Selangor, Malaysia
[d] School of Environmental and Natural Resource Sciences, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, Malaysia

ARTICLE INFO

Article history:
Received 21 March 2017
Received in revised form
29 August 2017
Accepted 31 August 2017
Available online xxx

Keywords:
Malaysia
Weed
Oil palm
Rubber
Rice

ABSTRACT

The agriculture sector remains a significant development factor in Malaysia. Oil palm and rubber are the two major crops contributing to national development in terms of export earnings, and rice is vital for the national food consumption. However, weeds continue to be an important constraint for oil palm, rubber, and rice production. Weed management in Malaysia is highly reliant on herbicides; however, other control measures are integrated, including cultural, physical, biological, and mechanical methods. Thus, herbicides accounted for 83% of the total pesticide usage in the year 2014. However, several limitations remain in weed control and these are influenced by several factors, such as labour shortage, evolution of herbicide resistance in weeds, constraints of new modern technology implementation, global climate change, poor policy support, inadequate infrastructure, and rising input costs. This paper explains a number of issues, challenges, and opportunities that are significant for the future role of weed management in the agriculture of Malaysia, especially for the oil palm, rubber, and rice industries.

1. Introduction

Agriculture is an important sector in Malaysia. Malaysia has broadened and diversified its economy through industrialization; however, the agriculture sector remains the backbone of the Malaysian economy. In 2015, the agriculture sector continued to expand and contributed 8.9% to the gross domestic product (Department of Statistics Malaysia, 2016). Moreover, the majority of agricultural lands are devoted to oil palm (*Elaeis guineensis* Jacq.), rubber (*Hevea brasiliensis* (Willd. ex A.Juss.) Müll.Arg.), and rice (*Oryza sativa* L.). Currently, Malaysia accounts for 39% of global oil palm production and 44% of global export (Malaysian Oil Palm Council, 2016). As the second largest oil palm producer in the world after Indonesia, Malaysia also ranks as the sixth largest producer of natural rubber in the world after Thailand, Indonesia, Vietnam, China, and India. Natural rubber production in Malaysia increased by 4.1% i.e from 0.67 million tons in 2014 to 0.72 million tons in 2015 (Department of Statistics Malaysia, 2016). Consumers consider Malaysia as a source of high-quality Standard Malaysian Rubber (SMR), raw grade rubber, specialty rubber, and latex concentrates, including low-protein latex. Unlike the oil palm and rubber industries that have contributed significantly to foreign exchange earnings, the rice industry in Malaysia is highly protected and the protection is explained largely by the arguments for food security. Milled rice production in Malaysia was 1.82 million MT in 2016 with an average yield of 4.03 t/ha (IRRI, 2017), and the total consumption for approximately 30.6 million people was 2.4 million MT (DOA, 2015). Thus, the government imported rice from various countries, such as Thailand, Myanmar, and Vietnam, to supplement the shortages in supply from domestic production.

Many factors have been identified for the low productivity of crops, such as the quality of soil and seeds, unpredictable weather, limitations in the use of new technologies, labour shortage, and inadequate and poorly maintained agricultural infrastructures (Baki, 2004; Kang et al., 2009). Disease outbreaks and insect pests are other contributing factors and are caused by insufficient biosecurity measures. Moreover, weeds affect crop production. However, the importance of weeds is usually ignored by farmers and government officials. The effects of weeds on oil palm and rubber are difficult to quantify due to their long economic life (20–30 y) (Kuan et al., 1991). However, Sahid et al. (1992) reported that yield losses in oil palm plantations are 6–20% because of strong competition from weeds. Kustyanti and Horne (1991) evaluated a

* Corresponding author.
E-mail address: dilip@mardi.gov.my (M. Dilipkumar).

http://dx.doi.org/10.1016/j.cropro.2017.08.027
0261-2194/

12% increase in fresh fruit bunch production in oil palm plantations by eliminating *Asystasia gangetica* (L.) T.Anderson. Weeds that infest oil palm and rubber plantations in Malaysia are generally from the same species (Asna and Ho, 2005). The prevalent woody broadleaf weeds are *Chromolaena odorata* (L.) R.M.King & H.Rob., *Oldenlandia verticillata* L., and *Melastoma malabathricum* L., which are found in most tropical countries (Husnatulyusra, 2012). Creeping broadleaf weeds, such as *Mikania micrantha* Kunth and *A. gangetica*, can reduce palm production (Asna and Ho, 2005; Husnatulyusra, 2012). The common erect and non-woody broadleaf weeds are *Cleome rutidosperma* DC. and *Spermacoce alata* Aubl. (Ismail et al., 1995). Ferns, such as *Gleichenia laevigata* (Willd.) Hook., *Lygodium* spp., *Stenochlaena palustris* (Burm.f.) Bedd., *Schizocaena molucana* (Desv.) Copel., and *Cyclosorus* spp., are generally found in oil palm plantations (Husnatulyusra, 2012). In contrast, *Imperata cylindrica* (L.) Raeusch., *Pennisetum purpureum* Shumach., *Paspalum conjugatum* P.J.Bergius., *Sorghum halepense* (L.) Pers., *Brachiaria mutica* (Forssk.) Stapf., *Chloris barbata* Sw., and *Ischaemum muticum* L. are grasses that infest oil palm and rubber plantations (Ismail et al., 1995; Ahmad Faiz, 2006). Sedges, such as *Cyperus compressus* L., *Cyperus distans* L.f., *Cyperus rotundus* L., and *Fimbristylis acuminata* Vahl., are commonly found in oil palm nurseries (Chung, 2013).

For rice production, about 90% of the rice fields in Malaysia are planted with direct-seeded rice and the rest is transplanted rice. Three principal methods are used for direct-seeded rice systems, namely, dry seeding, wet seeding, and water seeding (Chauhan, 2012). Water seeding requires rice cultivars that are tolerant to anaerobic soil conditions to attain optimal plant density, and this seeding system is unsuitable for water scarce areas. Meanwhile, dry seeding is conducive for germination and weed development due to the absence of standing water and bird damage susceptibility, which happens when the seeds are not covered well with soil after seeding. Due to these conditions, Malaysian farmers have adopted the wet-seeded rice culture since 1980, wherein pre-germinated rice seeds are sown on wet puddle soils. However, the wet-seeded rice system has its own limitation. Weed infestation is the major challenge for the production and adoption of wet-seeded rice system (Azmi et al., 2007). Rice yield losses caused by weeds reach 5–85% in Malaysia and depend on the planting method, season, location, predominant weed flora, weed density, management practices, and infestation duration (Azmi et al., 1993; Karim et al., 2004; Dilipkumar et al., 2012). Weed surveys have been performed in different rice granaries throughout the country (Azmi, 1990; Azmi et al., 1993; Azmi and Baki, 1995; Azmi and Mashhor, 1995; Ismail and Goh, 2003; Hakim et al., 2013). The common weeds identified in the surveys varied among locations. In general, weedy rice (*Oryza sativa* L.), *Echinochloa* spp., *Leptochloa chinensis* (L.) Nees., *Ischaemum rugosum* Salisb., *Paspalum* spp., *Digitaria ciliaris* (Retz.) Koeler., and *Cynodon dactylon* (L.) Pers. were the predominant grass weeds in direct-seeded rice (Azmi, 1990; Azmi et al., 1993; Azmi and Baki, 1995; Azmi and Mashhor, 1995). Broadleaves, such as *Limnocharis flava* (L.) Buchenau., *Monochoria vaginalis* (Burm.f.) C.Presl., *Sagittaria guayanensis* Kunth., *Eichhornia crassipes* (Mart.) Solms., *Ludwigia hyssopifolia* (G.Don) Exell., and *Sphenoclea zeylanica* Gaertn. and sedges, such as *Cyperus* spp., *Fimbristylis quinquangularis* (Vahl) Kunth., *Actinoscirpus grossus* (L.f.) Goetgh. & D.A.Simpson., are equally important weeds in the Malaysian direct-seeded rice ecosystem (Hakim et al., 2013; Azmi and Mashhor, 1995; Azmi and Baki, 1995).

Field crop growers, particularly in the oil palm and rubber industries, normally assume that weeds can be easily controlled by herbicides or mechanically, such as using a weed slasher or mower. This misinterpretation prevents effective weed management and weed science development. Effective weed control is essential for good crop production. This review article is the first to examine the current weed management practices of the oil palm, rubber, and rice industries in Malaysia. This country has relatively experienced various challenges in weed-related issues. However, opportunities and prospects are available to improve the weed management strategy in Malaysia. A detailed overview of the weed management scenario in Malaysia is presented in this paper. The information will allow scientists and policy makers to identify the knowledge and research gaps to mitigate the production costs and enhance production by improving weed management technologies.

2. Issues

2.1. Constraints experienced by smallholders

In general, independent and organized smallholders are the two types of farmers in Malaysia. Independent smallholders are growers who cultivate crops without direct assistance from the government or any private organization, whereas organized smallholders cultivate crops with support from either the government or any organization that provides technical assistance, agricultural input or financial support. Malaysia has more than 5.3 million ha of oil palm plantations, in which Peninsular Malaysia accounts for 55% of the total oil palm plantations, whereas Sabah and Sarawak collectively account for 45%. Among these planted areas, the estates account for 60% and the remaining areas are managed by smallholders (MPOB, 2014); moreover, about 90% of the rubber planted areas in Malaysia belong to smallholders and the remaining areas are under estates. Thus, smallholders have continued to contribute significantly to national oil palm and natural rubber production. For the two crops, weeds are the major biological constraints for production throughout these smallholder farming systems. Weed management costs in the oil palm industry comprise the costs to conduct circle weeding within the area covered by the crop canopy and clear the harvesting paths and planting rows; eradicate hard-to-control weeds with underground rhizomes; waxy leaves; and conduct selective weeding to control isolated colonies of weeds or small patches, which amount to 17% of total mature cultivation costs. Weed control is the second highest resource demand practice after manuring in oil palm cultivation (Chan and Yusof, 1998). Meanwhile, about 24–70% of the rubber field maintenance costs are consumed on weed control during the first two years of planting, and depends on the rubber plantation type (Chee, 1989; Mohamad Johari, 2003, 2005). Simultaneously, scattered and inefficient sizes of holdings have resulted in low oil palm and rubber productions. Hence, with an aged population of smallholders for the two crop cultivations, weed management is usually ignored because of limited institutional, technical and/or financial support, and insufficient knowledge regarding the best practices and new technologies; and the behaviour of a considerable number of smallholders who are not concerned about maintaining their fields. Rahman et al. (2008) confirmed that independent oil palm smallholders are less efficient than other producers due to their small plot size and poor agricultural practices. In contrast, about 57% of the rice production in Peninsular Malaysia is obtained from the 10 granary areas that implement double cropping with extensive irrigation and drainage facilities. The remaining 43% of smallholder farmers experience limited irrigation and poor land development due to limited modernization accessibility, which are the major factors for poor weed management.

2.2. Labour shortage

Labour shortage is another important issue in weed management. Youth from rural areas in Malaysia showed small interest in oil palm, rubber, and rice cultivations, and most of them have migrated to urban areas to acquire a good standard of living. This phenomenon leads to an increase in the employment of foreign workers. However, weed control for oil palm and rubber industries is usually ignored, regardless of smallholdings or estates, especially during crop (fresh fruit bunches or latex) harvest and collection, wherein these core activities are continuously prioritized. Rice farmers have focused on insect pests and disease management rather than weed management because of labour scarcity and rising wage rates.

2.3. High dependency on herbicides

Herbicides are frequently considered as a relatively straightforward way of ensuring rapid and cost-effective weed management in the oil palm and rubber industries. Direct seeding rice farming is highly dependent on herbicides for effective weed control (Jabran and Chauhan, 2015). According to FAOSTAT (2017), about 39,407 and 49,199 tons of active pesticide ingredients were used in Malaysia during 2006 and 2014, respectively. This statistic represented an annual average growth rate of 3.1% over the past 8 years for the nominal amount of agricultural pesticides used in the country. Among the agricultural chemicals, a large percentage (83%) of herbicide usage was reported during 2014 (FAOSTAT, 2017). These data showed that Malaysian farmers excessively relied on herbicides without considering their implications on human health and environment. However, the government has increased the public and consumer awareness on the herbicide usage. For example, Class I herbicides, such as paraquat, are recommended to be reduced or eliminated in oil palm plantations under the stewardship program of the Roundtable on Sustainable Oil palm (RSPO) (Rutherford et al., 2011), although a study initiated by the Malaysia Oil Palm Board suggested that the agricultural sector is still required to use paraquat for effective economic purposes (Wahid et al., 2011). Moreover, continuous usage of a particular herbicide may cause a shift in weed flora. Azmi and Baki (1995) observed that *Echinochloa crus-galli* (L.) P.Beauv. was dominant in direct-seeded rice plots with repeated application of 2,4-D amine, whereas *M. vaginalis* appeared in area where graminicides were frequently used. In another study, *Limnophila erecta* Benth. and *Bacopa rotundifolia* (Michx.) Wettst. were dominant in an important Sekinchan rice granary area due to continuous exposure to sulfonylurea herbicides (Azmi and Baki, 2003). Herbicide residues, such as propanil, thiobencarb, and pretilachlor, were detected in the soil and water of the rice fields because of frequent herbicide usage (Prayitno and Ismail, 2012). Hence, the herbicide dependency with same mode of action resulted in weed flora shifts, which brought new challenges for weed control in direct-seeded rice.

2.4. Evolution of herbicide resistance

High dependency on herbicides causes intense selection pressure, which leads to the evolution of herbicide resistance in many weed species. This phenomenon is intensified due to the monoculture of oil palm, rubber or rice. Four weed species, namely, *Eleusine indica* (L.) Gaertn. (Chuah et al., 2004), *Clidemia hirta* (L.) D.Don (Ramadzan et al., 2012), *O. verticillata* (Chuah et al., 2005), and *C. odorata* (Chuah and Ismail, 2009), which are found in oil palm plantations and/or nurseries have evolved resistance against herbicides in the states of Terengganu, Kelantan, Pahang, Kedah, Selangor, Perak, Johor, and Sarawak (Chuah and Ismail, 2010) (Table 1). Most of these weed biotypes are resistant to glyphosate, paraquat, and metsulfuron. *E. indica*, which is a problematic weed that grows on undeveloped oil palm plantations and nurseries, has evolved resistance to multiple herbicides, such as glyphosate, paraquat, glufosinate and/or fluazifop (Jalaluddin et al., 2010; Chuah et al., 2016). In contrast, *E. indica*, *O. verticillata*, and *I. rugosum* are resistant to paraquat and/or glyphosate, respectively, and these grow on rubber plantations and/or nurseries (Chuah and Ismail, 2010; Heap, 2017) (Table 1). According to Heap (2017), the evolution of resistant weeds in the rice ecosystem of Malaysia was first reported in 1989, and eight weed species, namely, *F. quinquangularis*, *S. zeylanica*, *L. flava*, *S. guayanensis*, *B. rotundifolia*, *L. erecta*, *L. chinensis*, and *E. crus-galli* were recognized to be resistant to several herbicide groups (Table 1).

2.5. Effects of climate change

The imminent factors in climate change are temperature, rainfall, and carbon dioxide (CO_2) concentration. According to the United Nations Development Report, CO_2 emissions in Malaysia increased by 221% during 1990–2004 (The Associated Press, 2007). Due to high greenhouse gas emissions, Malaysia has experienced temperature variations of 0.7 °C–2.6 °C and precipitation changes ranging from −30% to 30% (Baharuddin, 2007). In addition, Malaysia has experienced deficit and flooding rainfalls due to El Nino and La Nina. Generally, weeds have greater genetic diversity and variation than crops. Moreover, weeds exhibit fast growth and reproduction due to the effects of climate change. Few studies have been reported regarding the effect of climate change on weeds in oil palm and rubber cultivations. However, these climate changes are assumed to significantly affect rice production due to the high competition from weeds (Baharuddin, 2007; Mahmudul Alam et al., 2011). Theoretically, elevated CO_2 has positive effects on the competitiveness of C_3 plants with C_4 plants. However, this assumption is not constantly accurate (Fuhrer, 2003; Chandrasena, 2009). For instance, Alberto et al. (1996) reported that rice, which is a C_3 plant, has a competitive advantage over a C_4 weed (*E. glabrescens*) under an elevated CO_2 condition, whereas a C_4 weed (*E. glabrescens*) has a competitive advantage over rice when subjected to elevated CO_2 and temperature. This result indicated that C_3 plants have a disadvantage under hot and dry conditions, which leads to an energy-wasting process called photorespiration (Kozaki and Takeba, 1996; Chandrasena, 2009). However, C_4 plants do not undergo photorespiration due to a special mechanism that increases CO_2 levels for enzyme binding (Ziska and Bunce, 1993; Dukes, 2000). In contrast, Ziska et al. (2010) showed that the competitive ability of weedy rice is stronger than that of cultivated rice in elevated CO_2, thereby suggesting that the effects of climate change on the same species in the same ecosystem are expected to be complex. The effect of increased CO_2 levels on C_3 plants (e.g. weedy rice versus cultivated rice) may depend on the standard reaction of the plant species and their physiological and morphological characteristics.

3. Challenges and opportunities

3.1. Oil palm and rubber industries

Similar weed management methods with different approaches have been practised in the oil palm and rubber industries. Rice, as a semi-aquatic plant, has different growing environments; thus, challenges and opportunities for weed control in the rice production area in Malaysia are reviewed separately. Chemical herbicides constitute an important component of weed management for many oil palm and rubber growers, particularly when the management by other means is proven inadequate or not readily available by smallholders. Based on the list of herbicides registered for oil palm and rubber (Tables 2 and 3), current chemical control may not be sustainable because of the few varieties of herbicides. Among these

Please cite this article in press as: Dilipkumar, M., et al., Weed management issues, challenges, and opportunities in Malaysia, Crop Protection (2017), http://dx.doi.org/10.1016/j.cropro.2017.08.027

Table 1
Herbicide resistant weeds in the Malaysian oil palm, rubber and rice ecosystems (Chuah and Ismail, 2010; Rahman et al., 2010; Chuah et al., 2016; Heap, 2017).

Crop	Weed species	Herbicide group	Herbicide	Reported year
Oil palm	*Eleusine indica* (L.) Gaertn.	PS I electron diverter + glutamine synthase inhibitor + ACCase inhibitor + glycine	Paraquat + glufosinate + fluazifop + glyphosate	2009
		Glycine + PS I electron diverter	Glyphosate + paraquat	2010
		Glycine + ACCase inhibitor	glyphosate + fluazifop	2006
		Glycine	Glyphosate	2004
		PS I electron diverter	Paraquat	2005
	Clidemia hirta (L.) D.Don.	ALS inhibitor	Metsulfuron	2010
	Oldenlandia verticillata L.	PS I electron diverter + glycine	Paraquat + glyphosate	2005
	Chromolaena odorata (L.) R.M.King & H.Rob.	ALS inhibitor + synthetic auxin	Metsulfuron + triclopyr	2005
Rubber	*Eleusine indica* (L.) Gaertn.	PS I electron diverter	Paraquat	2005
		Glycine	Glyphosate	2006
	Oldenlandia verticillata L.	Glycine	Glyphosate	2005
	Ischaemum rugosum Salisb.	PS I electron diverter	Paraquat	1989
Rice	*Fimbristylis quinquangularis* (Vahl) Kunth.	Synthetic auxins	2,4-D	1989
	Sphenoclea zeylanica Gaertn.	Synthetic auxins	2,4-D	1995
	Limnocharis flava (L.) Buchenau.	ALS inhibitors	Bensulfuron	1998
		Synthetic auxins	2,4-D	
	Sagittaria guayanensis Kunth.	ALS inhibitors	Bensulfuron	2000
	Bacopa rotundifolia (Michx.) Wettst.	ALS inhibitors	Bensulfuron, metsulfuron, pyrazosulfuron	2000
	Limnophila erecta Benth.	Synthetic auxins	2,4-D	2002
		ALS inhibitors	Bensulfuron, metsulfuron, pyrazosulfuron	
	Leptochloa chinensis (L.) Nees	PS II inhibitor (ureas and amides)	Propanil	2006
	Echinochloa crus-galli (L.) P.Beauv.	PS II inhibitor (ureas and amides) + synthetic auxins + ACCase inhibitor	Propanil + quinclorac + cyhalofop-butyl	2010

Table 2
Herbicides used in oil palm cultivation at different growth stages of oil palm (adapted from Chung, 2013).

Oil palm growth stage	Herbicide active ingredient	Remark
Nursery	Glyphosate, fluazifop, glufosinate, metsulfuron, sodium chlorate, sodium chlorate + metsulfuron Paraquat + metsulfuron	Careful spraying using a spray shield
Replanting	Glufosinate, glyphosate, paraquat, sodium chlorate + metsulfuron, glyphosate + metsulfuron, sodium chlorate + metsulfuron	Blanket spraying before planting of oil palm and cover crops
Immature	Glyphosate, fluazifop, glufosinate, metsulfuron, sodium chlorate, 2,4-D	Selective spot spraying
(0–3 years)	Metsulfuron, fluazifop, glufosinate, sodium chlorate + metsulfuron, Paraquat + metsulfuron, diuron + paraquat, diuron + MSMA,	Circle spraying
	Imazethapyr, metsulfuron, paraquat, glufosinate	Suppression of leguminous ground cover
Mature (>3 years)	Paraquat + 2,4-D, sodium chlorate + metsulfuron, glyphosate + metsulfuron, paraquat + metsulfuron, glufosinate, diuron + MSMA	Circle and strip spraying
	Triclopyr, glyphosate, fluroxypyr, 2,4-D, sodium chlorate + 2,4-D, glyphosate + metsulfuron, paraquat + metsulfuron, sodium chlorate + metsulfuron	Selective spot spraying
	Sodium chlorate, paraquat	Suppression of natural ground covers
	Triclopyr, triclopyr + diesel (1:19 ratio), glyphosate + metsulfuron,	Epiphyte and broadleaved woody plant control
	Glyphosate + indaziflam	Circle spraying

Table 3
Recommended herbicides for weed control in young and mature rubber (adapted from Ahmad Faiz, 2007).

Type of weeds	Herbicide active ingredient
Grasses	
Non-noxious weed (e.g. *Eleusine indica* (L.) Gaertn., *Paspalum conjugatum* P.J.Bergius., *Ottochloa nodosa* (Kunth) Dandy., *Digitaria* sp.)	Glyphosate, glufosinate
Noxius weed (e.g. *Imperata cylindrica (L.)* Raeusch. *Pennisetum polystachion* (L.) Schult., *Ischaemum muticum* L.)	Glyphosate, imazapyr
Broadleaves	
Non-woody weed (e.g. *Spermacoce alata* Aubl., *Cleome rutidosperma* DC., *Mikania micrantha* Kunth., *Asystasia gangetica* (L.) T.Anderson.)	2,4-D, metsulfuron
Woody weed (e.g. *Melastoma malabathricum* L., *Clidemia hirta* (L.) D.Don., *Chromolaena odorata* (L.) R.M.King & H.Rob.)	Fluroxypyr, metsulfuron, triclopyr, picloram + 2,4-D
Mixture of grasses and broadleaves	Glyphosate, glyphosate + metsulfuron, glyphosate + 2,4-D, glyphosate + fluroxypyr, glufosinate
Ferns (e.g. *Dicranopteris linearis* (Burm.f.) Underw., *Nephrolepis biserrata* (Sw.) Schott., *Stenochlaena palustris* (Burm.f.) Bedd., *Lygodium flexuosum* (L.) Sw.)	Glufosinate, 2,4-D + sodium chlorate

herbicides, imazapyr, imazethapyr, diuron, and indaziflam, possess pre-emergence activities, whereas the others are post-emergence herbicides. Post-emergence herbicides, such as glyphosate, glufosinate, metsulfuron, and paraquat, are used frequently (Kuntom et al., 2007), whereas pre-emergence herbicides are not usually applied due to their high cost. Furthermore, the paraquat ban in Malaysia will aggravate the problem within a few years because paraquat is a common herbicide used either alone or in combination with other herbicides. Agrochemical companies are urged to develop several premixed herbicides, and substantial research are required to find suitable tank mixtures for the oil palm and rubber industries that provide a broad spectrum weed control and delay the evolution of herbicide resistance. In line with this effort, the list of recommended herbicides for weed control in the oil palm and rubber industries needs to be reviewed to expand the selection of herbicides that can be applied.

Considering the increasing number of resistant weed biotypes, securing diversity in weed management is a key factor for delaying or reversing the trajectory of herbicide resistance (Diggle and Neve, 2001; Goh and Mohd Nasaruddin, 2016; Gressel and Segel, 1990; Maxwell et al., 1990; Neve et al., 2003). In conjunction with this purpose, a detailed survey of herbicide resistance will provide comprehensive data on the distribution and frequency of herbicide-resistant weeds in oil palm and rubber. However, this effort might be wasted because of the limited funding from the government and private agencies. Therefore, the participation of agrochemical companies is crucial for creating an herbicide resistance database while investigating the development of new agrochemicals to preserve the sustainability of their products as an essential tool for agricultural technology in cropping systems.

To date, 12 weed biotypes have evolved herbicide resistance against the oil palm and rubber plantations or nurseries in Malaysia (Table 1). High resistance levels coupled with cross or multiple herbicide resistance in these weed biotypes and insufficient information on resistance mechanism have complicated the implementation of systematic weed control strategies (Chuah and Ismail, 2010). One crucial factor in herbicide resistance is the intensity of selection for an herbicide, in which the major determinant is the herbicide application rate. Using lower (than recommended) doses of herbicides has the potential to lead the rapid evolution of herbicide resistance in weeds (Manalil et al., 2011). Hence, effective stewardship programs should be developed to encourage herbicide use at full label rate to minimize the possibility of rapid low-dose-induced resistance evolution and ensure herbicide sustainability (Manalil et al., 2011).

Rotating herbicides and tank mixture usage should be practised to manage herbicide resistance. However, insufficient premixed herbicides or tank mixtures persist, and this strategy is effective in slowing down the evolution of herbicide resistance. Beckie and Rebound (2009) reported that mixtures are more effective than rotation in mitigating resistance evolution through herbicide selection. A mixture of herbicides can be effective to delay the resistance if the combined herbicides i) affect the same target weed, ii) have different target sites of action, iii) have the same persistence and iv) are degraded in different manners (Wrubel and Gressel, 1994). A mixture of a non-selective herbicide and a broadleaf herbicide can slow down the occurrence of herbicide resistance in broadleaf weeds. However, the mixture can fail in delaying the evolution of herbicide resistance in grass weeds. Mixing two herbicides without recognizing their compatibility is not recommended, because the two herbicides may act additively, synergistically or antagonistically. For example, glyphosate causes antagonism of glufosinate ammonium activity in a tank mixture (Bethke et al., 2013; Chuah et al., 2008). Hence, a possibility still exists for improving the chemical control strategy by introducing new active ingredients applied in combination with the existing herbicides in the market. Considerable research should be conducted to develop suitable tank mixtures or premixed herbicides to delay the evolution of herbicide resistance in weeds.

Although chemical control is applied, insufficient cultural practices such as exclusion or poor establishment of leguminous ground cover crops during new or re-planting of oil palm and rubber, lead to low success rates of weed control in the later growth stages of oil palm and rubber (Chee, 1981; Ismail and Chan, 2000). However, this limitation can be overcome by close supervision and monitoring as a crop cover is established in the field. Establishing cover crops in the field is a promising method that suppresses weed growth and emergence and fixes nitrogen, thereby aiding in increasing soil fertility; moreover, the residues of cover crops that accumulate at the later stage during crop maturity contributes to the increment of organic matter in soil and/or act as a selective weed control measure by releasing allelochemicals (Chee, 1981; Jabran et al., 2015; Inderjit and Keating, 1999; Ismail et al., 2016). Furthermore, using fast growing characteristic coupled with high yielding varieties or clones of oil palm and rubber will provide adverse conditions for weed growth, wherein early canopy closure among the individual plants reduces light penetration to the ground, thereby aggressively prohibiting weed growth. Continuous effort in discovering the best selected planting materials through plant breeding programs and molecular approaches is another significant opportunity to be investigated that will benefit industries.

Other weed control measures that have been integrated with chemical weed control in oil palm (Chung, 2013) and rubber (Ahmad Faiz, 1979; Kamaruzaman, 1988; Punnoose et al., 2000; Samarappuli et al., 1998; Wan Mohamed and Chee, 1976) include manual and mechanical weeding, cultural tactics (e.g. mulching, cover crop planting), and biological control (e.g. grazing by ruminants, such as sheep and cattle). Previous studies have shown that overall weeding cost can be reduced by 16–36% by sheep rearing in a rubber plantation (Rubber Research Institute of Malaysia, 1985) and by 5–69% through oil palm–cattle integration (Davendra, 2011) compared with chemical control. Several publications have revealed that integrated weed management (IWM) for sustainable oil palm and rubber production can be achieved through various chemical, cultural, mechanical, and biological approaches, including herbicides, hand weeding, mulch, high planting density, livestock grazing, cultivation of cover crops, and mechanical slashing, depending on the growth stage of the crops (Malaysian Rubber Board, 2009; Chee and Chung, 2016; Chung, 2013). However, developing and implementing an environmentally and economically feasible IWM program in the oil palm and rubber industries has remained challenging even with several modifications based on local conditions (e.g. land demography and culture of life) and sustainability benefits (Ismail, 1986; Kamaruzaman, 1988). In summary, integrated weed management strategies is not a common practice for the two crop cultivations. To boost the implementation of IWM program for the two crops, incentives can be provided to those who are willing to adopt IWM. Employing competent extension officers is crucial to raise the awareness of smallholders voluntarily through effective communication and participatory educational programs. The extension officer should be trained properly to achieve this goal. Another approach is to employ several dedicated farmers who have considerably accomplished remarkable work at field upkeep in their smallholdings, to serve as role models for other smallholders regarding sustainable weed management in Malaysia.

In contrast, earnings attached to the price of the commodity are inclined to be unstable because they are coupled with the increase of costs in labour and herbicides, and limit oil palm and rubber smallholders from performing field upkeep in a timely manner. In this aspect, support and assistance from various parties and institutes are important. For instance, the Wild Asia Group Scheme can provide technical advice, management support, and training to aid independent oil palm smallholders in complying with the RSPO standards and increase fresh fruit bunch productions (Nagiah and Azmi, 2012). Nchanji et al. (2016) demonstrated that intercropping oil palm with food crops during the undeveloped stage creates extra income and reduces weeding costs for smallholders. However, if crop selections or timing differences in crop life cycles are not managed correctly, the two crops will compete with each other for water and nutrient resources and exhibit negative production results (Brainard and Bellinder, 2004).

In rubber, the socioeconomic welfare of smallholders can be enhanced under limited resources/budgets by adopting innovative and advanced technologies (e.g. high-yielding clones and yield stimulants) and/or integrated farming systems (e.g. sheep-rearing, bee-keeping, cash-cropping, and mushroom cultivation) (Malaysian Rubber Board, 2016; Mohd Akbar and Zarawi, 2003; Mohd Ali et al., 1986; Mohd Yusoff et al., 1989; Rodrigo et al., 2005; Wan Mohamed and Chee, 1976). All these approaches are yet to be widely adopted, and incentives in terms of technical services and financial benefits will accelerate the implementation of these approaches by smallholders. In terms of governmental policy, proactive initiatives, such as providing the 'Rubber Production Incentives' will decrease the economic burden of rubber smallholders. This incentive will be paid by the Malaysian government to smallholders when a difference is found between the fixed rubber price and the average rubber price, that is, when the price of SMR 20 FOB falls approximately below USD 1.31 per kg or USD 0.52 per kg of cuplumps (viz. coagulated latex found in tapping cups) under the current economic conditions.

3.2. Rice industry

Malaysian rice farmers have adopted herbicides as the first selection because they considered chemical weed control as a yield increasing and risk reducing factor. In wet-seeded rice, weeds emerge simultaneously with rice seedlings and produce rapidly in moist soil. Therefore, pre-emergence or soil-applied herbicides are important to suppress the early emergence and growth of aggressive weeds, which share fertilizer and soil moisture with rice seedlings. Several pre-emergence herbicides are available in the Asian rice market, viz, oxadiazon, oxadiargyl, pendimethalin, pyrazosulfuron, pretilachlor, butachlor, and clomazone (Chauhan, 2012; Awan et al., 2016). However, two active ingredients, namely, pretilachlor with safener and premixed herbicide of imazapic + imazapyr that are dedicated to imidazolinone-tolerant rice variety, are officially registered as a rice pre-emergence herbicide under the Malaysian Pesticide Board. Continued use of the same active ingredient or mode of action of herbicide will contribute to the evolution of resistant weed populations (Powles and Gaines, 2016). Therefore, agrochemical companies should start introducing several pre-emergence herbicide products with different modes of action to the Malaysian rice market.

In contrast, several premixed post-emergence herbicides with multiple modes of action are available in the Malaysian rice market. However, the instructions on herbicide labels are complicated for farmers to comprehend and apply, which has led to the inappropriate selection of active ingredients or dosage and the evolution of resistant weeds. To reduce these misdemeanours, the product label should indicate the mode of action of the herbicide in a colour code to allow farmers to distinguish among similar products with different modes of action. This indicator is part of the labelling strategy for the overall management of the herbicide resistance problem. In addition, updating the current status of herbicide-resistant weed populations in the rice ecosystem of Malaysia is necessary because the last case was recorded in 2010 (Rahman et al., 2010). Monitoring herbicide resistance status through periodic surveys is crucial to facilitate rice farmers the implementation of effective chemical control strategies, thus slowing down the occurrence of herbicide resistance in weeds.

Herbicides are important in weed control in direct-seeded rice fields. However, not all weed problems are solved by using herbicides. The input subsidies provided by the Malaysian government to rice farmers have indirectly contributed to the excessive use of herbicides. The objective of this incentive is to reduce the increasing cost of rice production (Najim et al., 2007). In several circumstances, this scheme boosted the herbicide usage in weed-free or -less infested land, thereby preventing the IWM approach. Several farmers are unwilling to invest in herbicides due to their dependence on subsidy, which resulted to non-optimal spraying selection. The concept of IWM approach is not new to the rice industry, but the acceptance level of this approach is significantly poor in farmers. Many studies have been conducted for local adaptation. Several well-established IWM methods applied in Malaysian rice fields include the stale seedbed technique, in which the weeds are allowed to germinate and the emerged weed seedlings are killed using non-selective herbicides (Azmi, 2012); moreover, the high seeding rate favours rice more than weeds and increases production under weedy conditions (Azmi and Johnson, 2006). Other IWM methods are using high quality and weed-free seeds from certified source (Azmi, 2012), maintaining standing water to suppress weeds (Azmi and Baki, 2002) and herbicide rotation (Anwar et al., 2012). Weed problems are multi-pronged; therefore, IWM approaches provide significantly sustainable approaches for rice production.

Other important elements in the IWM are allelopathic or weed-competitive rice varieties and crop rotation. Rice cultivars with strong allelopathic potentials or weed competitiveness are considered low-cost safe tools for weed management, and these have been reported by many researchers (Dilday et al., 2000; Kong et al., 2011; Mahajan and Chauhan, 2013). Few studies in Malaysia have determined the competitive ability and allelopathic potential of traditional and modern rice varieties (Azmi et al., 2000; Karim and Ismail, 2003; Karim et al., 2012; Sunyob et al., 2015). Unfortunately, this issue has not been addressed by Malaysian rice breeding programs because they are focused on insect pests and diseases-resistant screening. The development of competitive or allelopathic rice cultivars requires a significant analysis of the mechanisms in which a rice genotype becomes competitive with weeds or is responsible for its allelopathic effects. With the aid of modern genetic techniques, the development of new rice cultivars with strong weed suppressing ability and cultivation acceptability by farmers will provide weed management alternatives in the near future.

On the other hand, crop rotation is considered a vital weed management tool because it affects weed demography and subsequent population dynamics (Buhler, 2002). However, the practice of double cropping in Malaysia led to maximizing rice production. The government has committed and implemented development projects for water resources and infrastructures for about 387,020 ha, which are known as granary areas, to enable rice planting during wet and dry seasons (DOA, 2015). However, these facilities are not available in non-granary areas and thus farmers are seriously affected during drought or dry season caused by El Nino. The government should encourage rice farmers in non-granary areas to cultivate non-rice crops (viz. maize, legumes, and vegetables) during the dry season when water resources are limited, to reduce the risk of drought and increase system productivity. The selection of crop rotation determines possible herbicide usage patterns, which significantly influences weed density and diversity (Stevenson and Johnston, 1999).

Weedy rice infestation threatened the rice production in Malaysia until the Clearfield® rice cultivar was introduced in 2010. Clearfield® rice, also known as imidazolinone (IMI)-tolerant rice, was developed through chemical mutagenesis and traditional breeding (Rajguru et al., 2005). Overall, Clearfield® technology has benefitted the rice industry in Malaysia by increasing yield potentials in weedy rice-infested areas from 3.5 metric tons/ha to 7 metric tons/ha (Sudianto et al., 2013). Despite this apparent advantage, natural hybridization between Clearfield® rice and weedy rice occurred because they are sexually and genetically compatible (Shivrain et al., 2007). Considering the potential risk of this technology, Clearfield® rice has been introduced in Malaysia along with a package consisting of Clearfield® certified seeds, OnDuty® herbicide (imazapic + imazapyr) and stewardship guidelines. Criticism has been received from local farmers regarding the failure of IMI herbicides in controlling weedy rice. Based on a preliminary survey, most farmers planted Clearfield® rice for more than two consecutive seasons and some were extended to seven seasons. Unfortunately, several farmers ignored the stewardship guidelines by purchasing uncertified seeds, spraying OnDuty® at inappropriate times or at reduced rates and cultivating Clearfield® rice without using OnDuty® or using unregistered IMI products. These factors may have resulted in the leakage of the resistance trait from Clearfield® rice to weedy or wild rice by natural hybridization. In such circumstances, enactment and enforcement of seed laws have become necessary in the rice industry to prevent fraud, counterfeiting, and bad quality seeds that are contaminated with weedy rice or carry diseases. In addition, strict adherence to the stewardship guidelines will be the key for continued success of herbicide tolerant rice technology in Malaysia.

4. Conclusions

Similarities and differences in weed management scenarios of oil palm, rubber, and rice cultivations in Malaysia have determined many control measures that should be implemented depending on intrinsic (weed biology, physiology, ecology, and genetics) and extrinsic (environmental conditions, socio-economics, and cropping systems) factors. Overall, chemical control has been widely used as a weed management tool in these crops. However, a possibility still exists in terms of introducing several types of herbicides, especially the pre-emergence and premixed herbicides, for effective weed control. Improved and additional tank mixtures with appropriate combination of herbicides should be developed to delay the evolution of herbicide resistance. Herbicide application in those cultivations is of significant importance; however, IWM implementation cannot be ignored. Hence, there is no single solution in combating weed management issues in oil palm, rubber, and rice cultivations in this country. As such, the development and implementation of a sustainable weed management that integrates cultural, mechanical, chemical, and biological tactics should not be the responsibility of farmers themselves. Involvement, cooperation, and support from all parties (policy makers, stakeholders, researchers, and herbicide manufacturers) are significant when designing an appropriate weed control strategy for enhanced crop health, production, and quality.

References

Ahmad Faiz, M.A., 1979. General principles of weed control. In: RRIM Training Manual on Crop Protection and Weed Control in Rubber Plantations. Rubber Research Institute of Malaysia, Kuala Lumpur, pp. 111–114.
Ahmad Faiz, M.A., 2006. Glyphosate and its mixtures against weeds under young rubber forests. J. Rubber Res. 9 (1), 50–60.
Ahmad Faiz, M.A., 2007. Weed control in rubber cultivation area. In: Rubber Cultivation Technology Manual. Malaysian Rubber Board, Kuala Lumpur, pp. 43–52.
Alberto, A.M., Ziska, L.H., Cervancia, C.R., Manalo, P.A., 1996. The influence of increasing carbon dioxide and temperature on competitive interactions between a C_3 crop, rice (*Oryza sativa*) and a C_4 weed (*Echinochloa glabrescens*). Aust. J. Plant Physiol. 23, 795–802.
Anwar, M.P., Juraimi, A.S., Puteh, A., Man, A., Rahman, M.M., 2012. Efficacy, phytotoxicity and economics of different herbicides in aerobic rice. Acta Agric. Scand. Sect. B 62 (7), 604–615.
Asna, B.O., Ho, H.L., 2005. Managing Invasive Species: the Threat to Oil-palm and Rubber - the Malaysian Plant Quarantine Regulatory Perspective. http://www.fao.org/docrep/008/ae944e/ae944e05.htm#bm05/ (accessed 16.01.17).
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 Prot. 83, 37–47.
Azmi, M., 1990. Weed flora in Selected Rice Granary Areas in Peninsular Malaysia. In: Lee, S.A., Kon, K.F. (Eds.), Proceedings of the Third Tropical Weed Science Conference, 4–6 December 1990. Malaysian Plant Protection Society, Kuala Lumpur, pp. 16–17.
Azmi, M., 2012. Weed succession and Management Technologies in Rice. Presented research inaugural lecture, 17 May 2012. MARDI, Serdang, Malaysia, p. 21.
Azmi, M., Abdullah, M.Z., Fuji, Y., 2000. Exploratory study on allelopathic effect of selected Malaysian rice varieties and rice field weed species. J. Trop. Agric. Food Sci. 28, 39–54.
Azmi, M., Baki, B.B., 1995. The succession of noxious weeds in tropical Asian rice fields with emphasis on Malaysian rice ecosystem. In: Sugiyama, et al. (Eds.), Proceedings of the 15th Asian Pacific Weed Science Society Conference, 24–28 June 1995. Asian Pacific Weed Science Society, Tsukuba, Japan, pp. 51–67.
Azmi, M., Baki, B.B., 2002. Impact of continuous direct seeding rice culture on weed species diversity in the Malaysian rice ecosystem. In: Proceedings of the Regional Symposium on Environment and Natural Resources, 10–11 April 2002, vol. 1. Hotel Renaissance, Kuala Lumpur, Malaysia, pp. 61–67.
Azmi, M., Baki, B.B., 2003. Weed species diversity and management practices in the Sekinchan Farm Block, Selangor South-West Project: a highly productive rice area in Malaysia. In: Casimero, M.C., Pablico, S.M., Janiya, J.D. (Eds.), Proceedings of the 19th Asian Pacific Weed Science Society Conference, Manila, Philippines, 17–21 March 2003. Asian Pacific Weed Science Society, Manila, pp. 174–184.
Azmi, M., Baki, B.B., Mashhor, M., 1993. Weed communities in Principal Rice Growing Areas in Peninsular Malaysia. MARDI Report No. 165, p. 15.
Azmi, M., Johnson, D.E., 2006. Crop establishment options for lowland irrigated rice in relation to weed infestation and grain yield. J. Trop. Agric. Food Sci. 37 (1), 111–117.
Azmi, M., Juraimi, A.S., Mohamad Najib, M.Y., 2007. Critical period for weedy rice control in direct-seeded rice. J. Trop. Agri. Food Sci. 35, 319–332.
Azmi, M., Mashhor, M., 1995. Weed succession from transplanting to direct-seeding method in Kemubu rice area, Malaysia. J. Biosci. 6 (2), 143–154.
Baharuddin, M.K., 2007. Climate change: its effects on the agricultural sector in Malaysia. In: National Seminar on Socio-economic Impacts of Extreme Weather and Climate Change, 21–22 June. Malaysia.
Baki, B., 2004. Invasive weed species in Malaysian Agro-Ecosystems: species, impacts and management. Malays. J. Sci. 23, 1–42.
Beckie, H.J., Rebound, X., 2009. Selecting for weed resistance: herbicide rotation and mixture. Weed Technol. 23, 363–370.
Bethke, R.K., Molin, W.T., Sprague, C., Penner, D., 2013. Evaluation of the interaction between glyphosate and glufosinate. Weed Sci. 61 (1), 41–47.
Brainard, D.C., Bellinder, R.R., 2004. Weed suppression in a broccoli-winter rye intercropping system. Weed Sci. 52 (2), 281–290.
Buhler, D.D., 2002. Challenges and opportunities for integrated weed management. Weed Sci. 50, 273–280.
Chan, K.W., Yusof, B., 1998. Challenges facing the oil palm industry- the plantation perspective, 2–11 November 1998. 18th Palm Oil Familiarization Programme, p. 18.
Chandrasena, N., 2009. How will weed management change under climate change? Some perspectives. J. Crop Weed 5 (2), 95–105.
Chauhan, B.S., 2012. Weed management in Directs Seeded Rice Systems. International Rice Research Institute, Los Baños, Philippines, p. 20.
Chee, Y.K., 1981. The importance of legume cover crop establishment in rubber cultivation in Malaysia. Colombia, South America. In: The International Workshop on Biological Nitrogen Fixation Technology for Tropical Agriculture, 9–13 March 1981, pp. 1–11.
Chee, Y.K., 1989. Use of new herbicides in immature rubber. In: Proceedings of the Rubber Research Institute of Malaysia Rubber Growers' Conference 1989, Malacca, Malaysia, 21–23 August 1989. Rubber Research Institute of Malaysia, Kuala Lumpur, pp. 451–462.
Chee, Y.K., Chung, G.F., 2016. Efficient Weed Management to Enhance Rubber Production. International Rubber Research and Development Board, Kuala Lumpur.
Chuah, T.S., Ismail, B.S., 2009. Status on Weed Resistance in Plantation Crops and Rice Fields in Malaysia. Paper presented at the Seminar on Weed Resistance: Status and management, 15 Jan 2009. Universiti Kebangsaan Malaysia, Selangor and Monsanto (M) Sdn Bhd.
Chuah, T.S., Ismail, B.S., 2010. The status of weed resistance in plantation crops of Malaysia. Planter 86, 615–620.
Chuah, T.S., Leong, S.Y., Low, V.L., Franci, A.J., Anne, M.K., Najihah, M.N.P., Thaneswary, N.P., Cha, T.S., 2016. The status of herbicide resistance in goosegrass from cultivation areas in Malaysia. In: 9th International Conference of Plant Protection in the Tropics, 3–5 August 2016. Hilton Hotel, Kuching, Sarawak, Malaysia.
Chuah, T.S., Noor-Zalila, M.R., Cha, T.S., Ismail, B.S., 2005. Paraquat and glyphosate resistance of Woody Borreria (*Hedyotis verticillata*) growing at oil palm plantations in Terengganu. Malays. Appl. Biol. 34 (2), 43–49.
Chuah, T.S., Salmijah, S., Teng, Y.T., Ismail, B.S., 2004. Changes in seed bank size and dormancy characteristics of the glyphosate-resistant biotype of goosegrass (*Eleusine indica* [L.] Gaertn.). Weed Biol. Manag. 4, 114–121.

Chuah, T.S., Teh, H.H., Cha, T.S., Ismail, B.S., 2008. Antagonism of glufosinate ammonium activity caused by glyphosate in tank mixtures used for control of goosegrass (*Eleusine indica* Gaertn.). Plant Prot. Q. 23 (3), 116–119.
Chung, G.F., 2013. Integrated management of weeds in oil palm plantations. In: Proceedings of 5th MPOB-IOPRI International Seminar, 22–23 Nov 2013. KLCC, Kuala Lumpur, Malaysia.
Davendra, C., 2011. Integrated tree crops-ruminants system in South Asia: advances in productivity enhancement and environmental sustainability. Asian–Australas. J. Anim. Sci. 24 (5), 587–602.
Department of Statistics Malaysia, 2016. Selected Agricultural Indicators. https://www.dosm.gov.my/v1/index.php?r=column/cthemeByCat&cat=72&bul_id=T2Z3NkhLSFk2VjZ5dkdUL1JQUGs4dz09&menu_id=Z0VTZGU1UHBUT1VJMFlpaXRRR0xpdz09/ (accessed 16.01.17).
Diggle, A.J., Neve, P., 2001. The population dynamics and genetics of herbicide resistance-a modeling approach. In: Powles, S.B., Shaner, D.L. (Eds.), Herbicide Resistance and World Grains. CRC Press, Boca Raton, Florida, pp. 61–99.
Dilday, R.H., Mattice, J.D., Moldenhauer, A.K., 2000. An overview of rice allelopathy in the USA. In: Kim, K.U., Shin, D.H. (Eds.), Rice Allelopathy. Kyungpook National University, Taegu, Korea, pp. 15–26.
Dilipkumar, M., Adzemi, M.A., Chuah, T.S., 2012. Effects of soil types on phytotoxic activity of pretilachlor in combination with sunflower leaf extracts on barnyardgrass (*Echinochloa crus-galli*). Weed Sci. 60, 126–132.
DOA, 2015. Booklet Statistik Tanaman: Sub-sektor Tanaman Makanan. pertanian.kedah.gov.my/images/pdf/Booklet_Statistik_Tanaman_Subsektor_Tanaman_Makanan_2015.pdf/ (accessed 28.12.16).
Dukes, J.S., 2000. Will the increasing atmospheric CO_2 concentration affect the success of invasive species? In: Mooney, H.A., Hobbs, R.J. (Eds.), Invasive Species in a Changing World. Island Press, pp. 95–113.
FAOSTAT, 2017. http://www.fao.org/faostat/en/#data/RP/(accessed 19.02.17).
Fuhrer, J., 2003. Agroecosystem responses to combinations of elevated CO_2, ozone, and global climate change. Agric. Ecosyst. Environ. 97, 1–20.
Goh, S.S., Mohd Nasaruddin, M.A., 2016. The paradigm for overreliance on herbicide in weed control: glyphosate-resistant *Echinochloa colona* as a model system. In: Proceedings Workshop of the IRRDB: Transfer of Technologies to Farmers for Sustainable Rubber Production, Yamoussoukro, Cote d'Ivoire, Africa, 28–30 September 2016. APROMAC, Abidjan, Cote d'Ivoire, Africa, pp. 41–42.
Gressel, J., Segel, L.A., 1990. Modelling the effectiveness of herbicide rotations and mixtures as strategies to delay or preclude resistance. Weed Technol. 4 (1), 186–198.
Hakim, M.A., Juraimi, A.S., Hanafi, M.M., Ismail, M.R., Selamat, A., 2013. A comparison of weed communities of coastal rice fields in Peninsular Malaysia. J. Environ. Biol. 34, 847–856.
Heap, I., 2017. The International Survey of Herbicide Resistant Weeds. http://www.weedscience.com/ (accessed 21.02.17).
Husnatulyusra, S., 2012. Diversity of Weed Flora in Different Stages of Oil Palm Plantation. Unpublished bachelor degree dissertation. Universiti Malaysia Sarawak, Sarawak, Malaysia.
Inderjit, Keating, K.I., 1999. Allelopathy: principles, procedures, processes, and promises for biological control. Adv. Agron. 67, 141.
IRRI, 2017. World Rice Statistics Online Query Facility. http://ricestat.irri.org:8080/wrsv3/entrypoint.htm (accessed 28.6.17).
Ismail, B.S., Chan, K.W., 2000. Integrated ground cover management in plantations. In: Yusof, B., Jalani, B.B., Chan, K.W. (Eds.), Advances in Oil Palm Research, vol. 1. Malaysian Oil Palm Board, pp. 623–652.
Ismail, B.S., Tasrif, A., Sastroutomo, S.S., Latiff, A., 1995. Weed seed populations in rubber and oil palm plantations with legume cover crops. Plant Prot. Q. 10 (1), 20–23.
Ismail, T., 1986. Integration of animals in rubber plantations. Agrofor. Syst. 4, 55–66.
Ismail, B.S., Goh, S.S., 2003. Quantitative assessment of weed flora and buried seeds of arable rice fields in the Muda Area, Kedah, Malaysia. J. Biosains 14 (2), 61–68.
Ismail, B.S., Syamin, H., Wan Juliana, W.A., Nornasuha, Y., 2016. Allelopathic potential of the leaf and seed of *Pueraria javanica* Benth. on the germination and growth of three selected weed species. Sains Malays 45 (4), 517–521.
Jabran, K., Chauhan, B.S., 2015. Weed management in aerobic rice systems. Crop Prot. 78, 151–163.
Jabran, K., Gulshan, M., Viender, S., Chauhan, B.S., 2015. Allelopathy for weed control in agricultural systems. Crop Prot. 72, 57–65.
Jalaluddin, A., Ngim, J., Bakar, B.H.J., Alias, Z., 2010. Preliminary findings of potentially resistant goosegrass (Eleusine indica) to glufosinate-ammonium in Malaysia. Weed Biol. Manag. 10 (4), 256–260.
Kamaruzaman, J., 1988. Influence of sheep grazing on soil chemical properties and growth of rubber *(Hevea brasiliensis)* in Malaysia. Agrofor. Syst. 7, 115–120.
Kang, Y., Khan, S., Ma, X., 2009. Climate change impacts on crop yield, crop water productivity and food security – a review. Prog. Nat. Sci. 19 (12), 1665–1674.
Karim, R.S.M., Azmi, M., Ismail, B.S., 2004. Weed problems and their management in rice fields of Malaysia: an overview. Weed Biol. Manag. 4, 177–186.
Karim, R.S.M., Ismail, B.S., 2003. Screening of Malaysian rice varieties for allelopathic potentiality. In: Roslan, S. (Ed.), Proceedings of the Bengkel Seminar IRPA- UKM Seminar. Universiti Kebangsaan Malaysia, Bangi, pp. 483–486.
Karim, R.S.M., Monowarul Momin, A.M.T.A., Mahfuza, B., 2012. Allelopathic potential of selected rice varieties. Afr. J. Biotechnol. 11 (88), 15410–15414.
Kong, C.H., Chen, X.H., Hu, F., Zhang, S.Z., 2011. Breeding of commercially acceptable allelopathic rice cultivars in China. Pest Manag. Sci. 67, 1100–1106.
Kozaki, A., Takeba, G., 1996. Photorespiration protects C_3 plants from photooxidation. Nature 384, 557–560.
Kuan, C.Y., Ann, L.S., Ismail, A.A., Leng, T., Fee, C.G., Hashim, K., 1991. Crop loss by weeds in Malaysia. In: Lee, S.A., Kon, K.F. (Eds.), Proceeding of the Third Tropical Weed Science Conference. MAPPS, Kuala Lumpur.
Kuntom, A., Ai, T.Y., Kamaruddin, N., Beng, Y.C., 2007. Pesticide application in the oil palm plantation. Oil Palm. Bull. 54, 52–67.
Kustyanti, T., Horne, P., 1991. The Effect of *Asystasia* on the Growth of Young Rubber in Polybags. http://pdf.usaid.gov/pdf_docs/PDABG454.pdf/ (accessed 13.2.17).
Mahajan, G., Chauhan, B.S., 2013. The role of cultivars in managing weeds in dry-seeded rice production systems. Crop Prot. 49, 52–57.
Mahmudul Alam, M.D., Siwar, C., Molla, R.I., Toriman, M.E., Talib, B., 2011. Climate change and vulnerability of paddy cultivation in North-West Selangor, Malaysia: a survey of farmers' assessment. Voice Acad. 6 (1), 45–56.
Malaysian Oil Palm Council, 2016. Malaysian Palm Oil Industry. http://www.mpoc.org.my/Malaysian_Palm_Oil_Industry.aspx/ (accessed 24.12.16).
Malaysian Rubber Board, 2009. Rubber Plantation and Processing Technologies. Malaysian Rubber Board, Kuala Lumpur.
Malaysian Rubber Board, 2016. MRB clone recommendation 2013. In: Proceedings of MRB-IRRDB Workshop on Agronomy and Transfer of Technology 2016, Park Avenue Hotel, Sungai Petani, Kedah, Malaysia, 26–28 April 2016. Malaysian Rubber Board, Kuala Lumpur, pp. 81–88.
Manalil, S., Busi, R., Renton, M., Stephen, B., Powles, S.B., 2011. Rapid evolution of herbicide resistance by low herbicide dosages. Weed Sci. 59 (2), 210–217.
Maxwell, B.D., Roush, M.L., Radosevich, S.R., 1990. Predicting the evoloution and dynamics of herbicide resistance in weed populations. Weed Technol. 4 (1), 2–13.
Mohd Akbar, M.S., Zarawi, A.G., 2003. Exploitation technologies in Malaysia. In: Proceedings of the International Workshop on Exploitation Technology, Kottayam, Kerala, India, 15–18 December 2003. Rubber Research Institute of India, Kottayam, Kerala, India, pp. 280–289.
Mohd Ali, S., Abu Bakar, A., Johani, M.Z., 1986. Bee-keeping under rubber. In: Rajarao, J.C., Amin, L.L. (Eds.), Proceedings of the Rubber Research Institute of Malaysia Rubber Growers' Conference 1986, Ipoh, Perak, Malaysia, 20–22 October 1986. Rubber Research Institute of Malaysia, Kuala Lumpur, pp. 296–306.
Mohamad Johari, M.H., 2003. Viability of Rubber Forest Plantation. Malaysian Rubber Board, Kuala Lumpur.
Mohamad Johari, M.H., 2005. Economics of Rubber Forest Plantation. Malaysian Rubber Board, Kuala Lumpur.
Mohd Yusoff, M.N., Mahmud, A.W., Bachik, A.T., Zainol, E., Norhayati, M., Mohd Johari, H., 1989. Intercropping under young rubber. In: Rajarao, J.C., Amin, L.L. (Eds.), Proceedings of the Rubber Research Institute of Malaysia Rubber Growers' Conference 1989, Ipoh, Perak, Malaysia, 20–22 October 1986. Rubber Research Institute of Malaysia, Kuala Lumpur, pp. 166–180.
MPOB, 2014. Economics & Industry Development Division -Malaysian Palm Oil Board.
Nagiah, C., Azmi, R., 2012. A review of smallholder oil palm production: challenges and opportunities for enhancing sustainability – a Malaysian perspective. J. Oil Palm Environ 3, 114–120.
Najim, M.M.M., Lee, T.S., Haque, M.A., Esham, M., 2007. Sustainability of rice production: a Malaysian perspective. J. Agric. Sci. 3 (1), 1–12.
Nchanji, Y.K., Nkongho, R.N., Mala, W.A., Levang, P., 2016. Efficacy of oil palm intercropping by smallholders. Case study in South-West Cameroon. Agrofor. Syst. 90, 509–519.
Neve, P., Diggle, A.J., Smith, F.P., Powles, S.B., 2003. Simulating evolution of glyphosate resistance in *Lolium rigidum*. I: population biology of a rare resistance trait. Weed Res. 43 (6), 404–417.
Powles, S.B., Gaines, T.A., 2016. Exploring the potential for a regulatory change to encourage diversity in herbicide use. Weed Sci. 64 (1), 649–654.
Prayitno, S., Ismail, B.S., 2012. Pollution levels of thiobencarb, propanil, and pretilachlor in rice fields of the Muda irrigation scheme, Kedah, Malaysia. Environ. Monit. Assess. 184, 6347–6356.
Punnoose, K.I., Kothandaram, R., Varghese, P., Jessy, M.D., 2000. Field upkeep and intercropping. In: George, P.J., Kuruvilla Jacob, C. (Eds.), Natural Rubber: Agromanagement and Crop Processing. Rubber Research Institute of India, Kottayam, India, p. 157.
Rahman, A.K.A., Abdullah, R., Shariff, F.M., Simeh, M.A., 2008. The Malaysian palm oil supply chain: the role of the independent smallholder. Oil Palm. Ind. Econ. J. 8 (2), 17–27.
Rahman, M.M., Ismail, B.S., Juraimi, A.S., 2010. Study on resistant biotypes of *Echinochloa crus-galli* in Malaysia. Aust. J. Crop Sci. 4 (2), 107–115.
Rajguru, S.N., Burgos, N.R., Shivrain, V.K., Stewart, J.M.D., 2005. Mutations in the red rice ALS gene associated with resistance to imazethapyr. Weed Sci. 53, 567–577.
Ramadzan, A.M.N., Ismail, B.S., Chuah, T.S., 2012. A preliminary report on the potential resistance of a soapbush (*Clidemia hirta* (L.) D.Don.) biotype to metsulfuron-methyl in an oil palm plantation in Jerantut, Malaysia. Plant Prot. Q. 27 (2), 64–69.
Rodrigo, V.H.L., Stirling, C.M., Silva, T.U.K., Pathirana, P.D., 2005. The growth and yield of rubber at maturity is improved by intercropping with banana during the early stage of rubber cultivation. Field Crop Res. 91, 23–33.
Rubber Research Institute of Malaysia, 1985. Sheep integration under rubber. Planter's Bull. 183, 36–41.
Rutherford, M., Flood, J., Sastroutomo, S.S., 2011. Roundtable for Sustainable Palm Oil (RSPO): Research Project on Integrated Weed Management Strategies for Oil Palm. Final report, p. 189.

Sahid, I., Hamzah, A., Aria, P.M., 1992. Effect of paraquat and alachlor on soil microorganism in peat spil. Pertanika 15, 121–125.

Samarappuli, L., Yogaratnam, N., Karunadasa, P., Mitrasena, U., 1998. Effects of mulching with rice straw on soil chemical properties and its influence in the performance of *Hevea*. J. Rubb. Res. 1 (4), 263–277.

Shivrain, V., Burgos, N., Anders, M., Rajguru, S., Moore, J., Sales, M., 2007. Gene flow between Clearfield™ rice and red rice. Crop Prot. 26, 349–356.

Stevenson, F.C., Johnston, A.M., 1999. Annual broadleaf crop frequency and residual weed populations in Saskatchewan Parkland. Weed Sci. 47, 208–214.

Sudianto, E., Beng-Kah, S., Ting-Xiang, N., Saldain, N.E., Scott, R.C., Burgos, N.R., 2013. Clearfield® rice: its development, success, and key challenges on a global perspective. Crop Prot. 49, 40–51.

Sunyob, N.B., Juraimi, A.S., Hakim, M.A., Man, A., Selamat, A., Alam, M.A., 2015. Competitive ability of some selected rice varieties against weed under aerobic condition. Int. J. Agric. Biol. 17, 61–70.

The Associated Press, 2007. http://www2.irrawaddy.com/article.php?art_id=9454/ (accessed 18.02.17).

Wahid, M.B., Kushairi, A., Shariff, F., Kuntom, A., Kamarudin, N., Mohammed, A.T., 2011. Paraquat: Asset or Liability: a Study Initiated by the Malaysian Palm Oil Board. Malaysian Palm Oil Board, Ministry of Plantation Industries and Commodities, Malaysia, p. 316.

Wan Mohamed, W.E., Chee, Y.K., 1976. Maximizing returns in immature rubber smallholdings. In: Proceedings of the Rubber Research Institute of Malaysia Planters' Conference 1976, Kuala Lumpur, Malaysia, 14–16 October 1976. Rubber Research Institute of Malaysia, Kuala Lumpur, pp. 34–43.

Wrubel, R.P., Gressel, J., 1994. Are herbicide mixtures useful for delaying the rapid evolution of resistance? A case study. Weed Technol. 8, 635–648.

Ziska, L.H., Tomecek, M.B., Gealy, D.R., 2010. Evaluation of competitive ability between cultivated and red weedy rice as a function of recent and projected increases in atmospheric CO_2. Agron. J. 102, 118–123.

Ziska, L.W., Bunce, J., 1993. Inhibition of whole plant respiration by elevated CO_2 as modified by growth temperature. Physiol. Plant 87, 459–466.

Please cite this article in press as: Dilipkumar, M., et al., Weed management issues, challenges, and opportunities in Malaysia, Crop Protection (2017), http://dx.doi.org/10.1016/j.cropro.2017.08.027