Resistant Weed Management in Plantation Crops*

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Herbicides remain the major strategy for weed control in plantation crops. Herbicide-resistant weed populations are evolving rapidly as a result of selection pressure imposed by heavy reliance on herbicide. Currently, four weed species namely Eleusine indica, Oldenlandia verticillata, Clidemia hirta *and* Chromolaena odorata *have been documented to have evolved resistance to single or multiple herbicides in plantation crops of Malaysia. This paper gives the best weed management practices and recommendations in plantation crops to reduce the risks of herbicide resistance. Mitigating the evolution of herbicide resistance is dependent on reducing the herbicide selection pressure through diversified weed management practices. Programmes for herbicide-resistance management must consider use of all cultural, mechanical, and chemical options available to minimise the spread of resistant plants and to eliminate additions of weed seed to the soil seedbank. The development and implementation of a sustainable resistant weed management should involve cooperation, and support from policy-makers, stakeholders, researchers, and herbicide manufacturers for enhanced crop health, production, and quality.*

Keywords: *Diversified weed management, field scouting, oil palm, resistance mechanism, rubber.*

Herbicide application still remains the major strategy for weed control in plantation crops of Malaysia although biological, mechanical and cultural methods are being practiced. Herbicides are frequently considered as a relatively straightforward way of ensuring rapid and cost-effective weed management in plantation crops. About 39,407 and 49,199 tonnes of active pesticide ingredients were used in Malaysia during 2006 and 2014, respectively (FAOSTAT, 2017). Among the agricultural chemicals, the herbicide accounted for 83 per cent of the total pesticide usage during 2014 (FAOSTAT, 2017).

EVOLUTION OF HERBICIDE-RESISTANT WEED

High dependency on herbicides as the primary method of weed control in plantations of Malaysia has resulted in the evolution of herbicide-resistant weeds. Herbicide resistance is defined as the naturally occurring inheritable ability of certain weed biotypes within a population to survive a herbicide treatment that would, under normal conditions of use, effectively control that weed population (Heap, 1997). Selection pressure of the herbicide can result in the evolution of the resistant biotypes

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eventually. Cross herbicide resistance is where a weed biotype is resistant to two or more herbicides due to the presence of a single resistance mechanism. Multiple herbicide resistance refers to situations where resistant plants possess two or more distinct resistance mechanisms. Selection causing change in weed populations begins when a small number of plants within a weed species have a genetic makeup that enables them to survive a particular herbicide application. The resistant biotype, therefore, is present in low numbers in natural populations and when a herbicide is applied, most of the susceptible biotype would die but the few resistant biotypes would survive, mature, and produce seeds. When the same herbicide is applied repeatedly and the resistant biotypes reproduce, the percentage weed population that is resistant will increase gradually (Gunsolos, 2008).

Heavy reliance 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 plantation crops in Malaysia. To date, 12 weed biotypes have evolved herbicide resistance in the oil palm and rubber plantations or nurseries in the country. Four weed species, namely, *Eleusine indica* (L.) Gaertn. (Chuah *et al.*, 2004), *Oldenlandia verticillata* L. (Chuah *et al.*, 2005), *Chromolaena odorata* (L.) R.M.King and H.Rob (Chuah & Ismail, 2010) and *Clidemia hirta* (L.) D.Don (Ramadzan *et al.*, 2012) which are found in oil palm plantations and/or nurseries, have evolved resistance against herbicides in the states of Pahang, Kedah, Selangor, Perak, Johor, and Sarawak, Terengganu, Kelantan, (Chuah & Ismail, 2010). Most of these weed biotypes are resistant to paraquat, glyphosate, and metsulfuron. *E. indica*, which is a problematic weed that grows on young 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 *Ischaemum rugosum* Salisb. which grow on rubber plantations and/or nurseries are resistant to paraquat and/or glyphosate, respectively (Chuah & Ismail, 2010; Heap, 2018).

SCOUTING AFTER HERBICIDE APPLICATION

Scouting is helpful in documenting changes in the weed population that occur over time in response to land management practices, including the evolution of herbicide-resistant weeds. Timely scouting and maintaining an inventory of weed species, distribution pattern, density, and size allow for subsequent assessment of the effectiveness of prescribed practices (Norsworthy *et al.*, 2012). Everman *et al.* (2011a) stated that scouting weeds after application of a herbicide should be carried out 7 to 14 days after each herbicide application and near harvest. It is of importance to determine if the plants that are present survived a previously applied herbicide or emerged after the last herbicide application by observing individual plant responses and checking previous field history to understand what changes may be occurring.

There are some observations in the field which are unlikely correlated to herbicide resistance. For instance, the presence of multiple weed species where a uniform response of individuals within a population is observed and the spatial pattern of plants remaining in the field are likely due to sprayer skips. Weed shifts occurring through the repeated use of similar herbicide is not related to herbicide resistance because a certain weed species becomes dominant due to selection for species that are tolerant to that herbicide (Everman, *et al.*, 2011a). However, there are some trends that suggest the presence of herbicide-resistant weeds and justify further investigation. For example, a single weed species labelled for control by a herbicide is present whereas all other weed species on the label are controlled after herbicide application. The spatial pattern of surviving weeds is random or consists of multiple plants within a patch. In high-level herbicide resistance, plants either die or uninjured with few plants having intermediate responses whereas in low-level herbicide resistance, a continuum of plant responses from slightly injured to nearly dead is observed with the majority of plants displaying an intermediate herbicide response early in the evolution of the population (Everman *et al.*, 2011a).

CONFIRMING HERBICIDE RESISTANCE

Confirmation of herbicide resistance in weed can be conducted in the field and in the greenhouse. Testing in the field is an option for growers when involving post emergence foliar herbicides. Field test has advantage over greenhouse test in terms of screening time but it may be less accurate because the weeds are larger and there is greater biotic and abiotic variability in the field. Greenhouse testing is the best method for confirming herbicide resistance in a weed species with no history of resistance, in a weed species suspected of having resistance to multiple herbicides, and when laboratory tests are not available (Burgos *et al.*, 2013).

Field testing should be conducted within 10 to 14 days of the application that the weeds survived. If more than 20 per cent to 40 per cent of the re-sprayed plants at recommended rate and twice the recommended rate in the field survived, while greater than 90 per cent of plants died in the previously unsprayed area, then a herbicide-resistant population may be present in the field (Everman *et al.*, 2011a). A greenhouse test can be carried out by collecting seeds from mature weeds in the field suspected of being herbicide-resistant and generating plants from these seeds in the greenhouse. Plants are sprayed with the herbicide of interest at three to four-leaf stage for post emergence foliar herbicide whereas germinated seeds are treated for soil applied herbicide. The comparison should be made among the responses of the suspected herbicide-resistant population and a known herbicide-susceptible population (Chuah *et al.*, 2010).

RESISTANT WEED MANAGEMENT

The best strategies to manage herbicide resistance are diversified weed management through mechanical, cultural, and biological tactics in addition to herbicides. There are two general approaches to decision making in managing herbicide-resistant weeds. Decisions based on a proactive management approach implement tactics before herbicide-resistant weeds are apparent, while decisions based on a reactive management approach implement tactics after herbicide resistance has been confirmed in the field (Norsworthy *et al.*, 2012).

Proactive management

Proactive weed management is a style of decision-making that anticipates events or changes in the field, plans ahead for them. Weed management planning needs to include the potential for weeds to become resistant to herbicides within the current management programme. Planters that use proactive management understand that weeds and herbicide resistance are largely a consequence of management decisions. They plan for short- and long-term events, they work closely with local agronomists to anticipate changes in the field, and they are willing to try new ideas (Everman *et al.*, 2011b).

Proactive management of herbicide-resistant weeds is critical for the long-term sustainability of effective herbicide options in plantation crops. There are several advantages of proactive management, including the abilities to preserve crop yield potential; save money compared with reactive methods; prevent the need for dramatic, short-term shifts in farm practices; and protect herbicide options for the future. Weed management decisions based on proactive management can be more cost-effective over time compared with programmes based on reactive management (Everman *et al.*, 2011b). For example, glyphosate-resistant goosegrass, in oil palm plantations. A possible proactive management programme consists of diuron and flumioxazin applied as pre emergence, followed by glyphosate applied post emergence. All three of these products have different mechanisms of action, and have overlapping activity on goosegrass. A reactive management programme, implemented once glyphosate-resistant goosegrass are present in the field, requires an additional product, glufosinate, applied postemergence to control emerged goosegrass. This additional product results in the reactive programme costing more than the proactive programme.

Diversified weed management is an important component of sustainable, long-term agricultural production. A combination of weed management tactics helps to reduce the risk of selecting herbicide-resistant weeds. Several crop management strategies, including herbicide tactics, mechanical tactics and cultural tactics should be used to build a diversified weed management programme.

Herbicide tactics

The choice of which herbicides to use requires careful planning for reducing the risk of herbicide resistance. Diverse herbicide use is achieved by applying several herbicides with different mechanisms of action and activity on the same target weed or weeds to delay the onset of herbicide-resistant weeds (Wrubel & Gressel, 1997). In conjunction with this purpose, the product label should indicate the mode of action of the herbicide in a colour code to allow growers to distinguish among similar products with different mechanism of action (Dilipkumar *et al.*, 2017a). This indicator is part of the labelling strategy for the management of the herbicide-resistant weed. Rotating herbicides and tank mixture usage should be practiced to manage herbicide resistance. Beckie and Rebound (2009) reported that mixtures are more effective than rotation in mitigating resistance evolution through herbicide selection. Herbicides may be combined as a mixture, or sequentially. A recent field study has demonstrated that a combination of 720 g a.i. per hectare glyphosate and 50 g a.i. per hectare indaziflam could reduce seedbank and regrowth of weeds in oil palm circle weeding area effectively (Sidik *et al.,* 2018). However, mixing two herbicides without recognising their compatibility is not recommended, because the two herbicides may act additively, synergistically or antagonistically, especially post emergence foliar herbicides. For example, glyphosate causes antagonism of glufosinate ammonium activity in a tank mixture (Bethke *et al.*, 2013; Chuah *et al.*, 2008).

Herbicide mixtures contain more than one active ingredient. Mixtures may include the use of two soil residual products, a soil residual product plus a foliar active product, or two foliar active products. Herbicide mixtures may be marketed as premix products. It is imperative that we follow all guidelines on the product labels when mixing and applying herbicides, and especially to use the full labelled rates for each product in a mixture. Using lower (than recommended) doses of herbicides has the potential to lead the rapid evolution of herbicide resistance in weeds (Manalil *et al.*, 2011). Low rates are defined as those that may provide effective control at an individual location but will not provide consistent control over a wide range of conditions. There are many ways by which weeds are exposed to low rates that are not related to the intended application of low rates. These include: spraying plants that are larger or at a more advanced growth stage than recommended on the herbicide label, inadequate coverage of weeds because of size, density and/or crop cover, or problems with sprayer calibration, faulty or ineffective equipment, and mixing (Everman *et al.*, 2011b).

Based on the list of herbicides registered for plantation crops in Malaysia, current chemical control may not be sustainable because of the few varieties of herbicides. Among these herbicides, oxyfluofen, imazapyr, imazethapyr, flumioxazin, diuron, bromacil, atrazine, ametryn and indaziflam, possess pre-emergence activities, whereas post-emergence herbicides are, 2,4-D, DSMA, MSMA, MCPA, aminopyralid, dicamba, clethodim, fluazifop, topramezone, fluroxypyr, triclopyr, glyphosate, glufosinate, metsulfuron, sodium chlorate and paraquat (*Table 1*). Post-emergence herbicides, such as glyphosate, glufosinate, metsulfuron, 2,4-D 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. 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. Agrochemical companies are urged to develop several premixed herbicides, and substantial research are required to find suitable tank mixtures for the plantation crop 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 plantation crop industries needs to be reviewed to expand the selection of herbicides that can be applied.

Mechanical tactics

Mechanical tactics are an additional part of proactive management that can be used to delay the evolution of herbicide-resistant weeds. Mechanical weed control can be performed with pre-plant tillage, in season with the form of mowing. It has been documented that sequential application of slashing and glyphosate at 1.83 kg a.i. per hectare provided at least 70 per cent reduction of node production, sprouting of nodes, stolon number, stolon length and viable stolon of drought grass under glasshouse conditions. Field experiment further revealed that slashing followed by two sequential application of glyphosate at 1.83 kg a.i. per hectare reduced total density and dry weight of drought grass by 58 per cent and 54 per cent respectively, as compared with untreated plots at three months after treatments in a coconut plantation (Dilipkumar *et al.*, 2017b). On the other hand, if small patches of weeds are present in an area known to have

TABLE 1

LIST OF HERBICIDES REGISTERED FOR PLANTATION CROPS

		Types of plantation crops			
Oil palm	*Rubber*	*Cacao*	*Coconut*	*Pineapple*	*Pepper*
2,4-D	2,4-D	glyphosate	2,4-D	paraquat	glyphosate
glyphosate	glyphosate	metsulfuron	glyphosate	atrazine	paraquat
paraquat	metsulfuron	ametryn	paraquat	bromacil	glufosinate
metsulfuron	diuron	glufosinate		ametryn	
diuron	ametryn	sodium chlorate	glyphosate +	diuron	
dicamba	dicamba	2,4-D	2,4-D		
glufosinate	glufosinate	fluroxypyr			
sodium chlorate	imazapyr	paraquat			
fluazifop	oxyfluorfen	fluazifop			
fluroxypyr	paraquat	MSMA			
MSMA	fluroxypyr				
imazapyr	fluazifop				
imazethapyr	sodium chlorate				
flumioxazin					
oxyfluorfen	MSMA				
indaziflam	triclopyr				
MCPA					
clethodim	glyphosate +				
topramezone	metsulfuron				
triclopyr	glyphosate +				
ametryn	triclopyr				
	glyphosate +				
glyphosate	imazapyr				
+ metsulfuron	glyphosate +				
glyphosate +	aminopyralid				
2,4-D	glyphosate +				
glyphosate +	MCPA				
imazapyr	glyphosate +				
glyphosate +	2,4-D				
triclopyr	MSMA +				
glyphosate +	diuron				
MCPA	MSMA +				
glyphosate +	diuron +				
aminopyralid	2,4-D				
aminopyralid +	DSMA +				
triclopyr	diuron +2,4-D				
MSMA +					
diuron					
MSMA +					
diuron + 2,4-D					
DSMA +					
diuron + 2,4-D					

herbicide resistance, hand-rogueing before seed set can prevent the build-up of herbicide-resistant weed populations. Weeds and weed seeds can be spread from one field to another on equipment. Equipment sanitation is important to slow the spread of herbicide-resistant weeds and weed seeds (Everman *et al.*, 2011b).

Cultural tactics

Cultural practices greatly influence the composition of weed populations, and their germination and growth. These practices can also influence the amount of weed seed in the seed bank and the spread of herbicide-resistant weeds. Cultural tactics involve the manipulation of agronomic practices to suppress weed growth while favouring growth of the crop. Appropriate fertiliser placement and crop residue management can increase the competitiveness of crops against weeds. Leguminous cover crops, sown prior to the plantation crop, could suppress weed growth through their physical presence or through the release of substances that affect the germination and growth of some weed species (Ismail *et al.*, 2016). Samedani *et al.* (2015) reported that cover crop management systems have potential to be included in sustainable oil palm plantation to reduce the use of herbicides. The study also suggest that *Axonopus compressus* could be considered as a suitable candidate as a cover crop under oil palm. The importance of preventing the movement of weed seeds and vegetative propagules, for and managing weeds in field borders is often overlooked as a means of slowing the spread of herbicide-resistant weeds. Managing weeds of concern in the borders is important if it is done before flowering to prevent pollen movement between herbicide-resistant and susceptible plants. The inspection and cleaning of equipment between field, has been shown to slow the spread of herbicide-resistant weeds (Everman *et al.*, 2011b).

Reactive management

Reactive management is a style of decision-making that acts in response to events or changes in the field when they occur with little to no expectation or anticipation of the events or changes. Ideally, we all start out trying to be proactive. We make plans and then somewhere we run into an unexpected situation. A reactive action is a response to an unexpected problem (Everman *et al.*, 2011b). Reactive management can be deployed during two general action times: tactics used within the same season a weed population has been identified as herbicide-resistant, or tactics used in seasons after the herbicide-resistant weed population has been identified. The initial timing of reactive management tactics may affect the intensity and number of options necessary to manage the herbicide-resistant weeds in the future. For example, early implementation will reduce weed densities in subsequent years and can reduce weed management costs in later years (Everman *et al.*, 2011b).

Same season management tactics are g l or hand-rogueing may be the primary mechanical options in some environments and geographies or when the herbicide-resistant population is small. In general, these options are limited in their effectiveness because of weeds and/or crop stage limitations later in the season (Everman *et al.*, 2011b).

High resistance levels coupled with cross or multiple herbicide resistance in weed biotypes and insufficient information on resistance mechanism could have complicated the implementation of reactive management (Chuah & Ismail, 2010). Mechanisms of resistance to herbicides can be divided into two groups: target-site and non-target-site mechanisms. Target-site resistance occurs due to mutations in the genes of the encoding proteins, when they are targetted by the herbicide. These include changing the binding sites of herbicide or by overproduction of the target enzyme due to gene overexpression or amplification. On the other hand, non-target site resistance could minimise the amount of active herbicide reaching the target through decreased foliar uptake or translocation out of treated sections, increased herbicide sequestration, or enhanced herbicide metabolism (Yuan *et al*., 2007).

Understanding the resistance mechanism is of prime importance in developing new, innovative and effective weed management approaches. The common approach generally adopted after the discovery of herbicide resistance is replacement with other herbicides that have different mechanisms of action. This strategy is effective when the particular weed biotype resistance is due to mutations at the site of action. However, it is not effective when the resistance mechanism involves enhanced metabolism that can cause detoxification of different groups of herbicides. In this case, deactivation of herbicide-metabolising enzymes with organophosphate insecticides may be effective for controlling resistant weeds due to enhanced metabolism mechanism (Busi *et al*., 2017). If the weed resistance is due to decreased uptake, the addition of appropriate adjuvant into the herbicide will restore the herbicide susceptibility of the resistant plants. Besides, the use of RNA interference (RNAi) technology, an innovative technology in the early stages of development has potential to combat herbicide resistant weeds. Reddy and Jha (2016) reported that the use of RNAi involves the topical application of double-stranded RNA (dsRNA) to interfere with the expression of herbicide resistance genes in weeds to reverse the resistance. RNAi is a revolutionary technology for resistant weed management, but is still years away from commercialisation

CONCLUSIONS

Mitigating the evolution of herbicide resistance is dependent on reducing the herbicide selection pressure through diversified weed management practices. Management diversity can be achieved by applying herbicides in mixtures, sequences, or rotation coupled with mechanical and cultural methods. Proactive management can be more cost effective and provide greater yield protection and income *versus* waiting to implement reactive strategies after herbicide-resistant weed populations are identified. The development and implementation of a sustainable resistant weed management should involve cooperation, and support from policy-makers, stakeholders, researchers, and herbicide manufacturers for enhanced crop health, production, and quality.

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