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Seventy-five years of synthetic herbicide use in agriculture: Will there be 100?

Herbicide use history and weed management in Southeast Asia

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Abstract: Southeast Asia's rich natural resources and favorable climatic conditions make it conducive for intensive rice-based, corn-based and perennial crops-based cropping systems. Regardless of the cropping system, weeds remain to be among the major factors that limit yields. The use of herbicides to manage weeds in these systems has been increasing through the years. The use of 2,4-D started in the late 1940s and remains as a major herbicide to control rice weeds. The 1980s saw the introduction of multiple active ingredients of herbicides for rice, corn and perennial crops, mostly selective herbicides with highly specific target sites and MOA. Glyphosate, commonly used in perennial crop-based systems, is now used at pre-planting in rice and corn and post-emergence in genetically modified corn. The intensive and continuous use of herbicides resulted in resistance development in weeds. To date, 37 unique cases of herbicide resistance are reported involving 17 weed species and 30 active ingredients. The rise in herbicide resistance and environmental pollution is largely due to insufficient farmer education on proper use of herbicides and integrated weed management, poor product stewardship, and lax implementation of pesticide policies and regulations. A sustainable weed management approach that embraces integrated and precise weed management is needed. We propose a sustainable weed management framework involving the various stakeholders to strengthen partnership, improve implementation and formulation of fair policies and regulations for the industry, increase investment in research and development of appropriate weed control technologies, and educate farmers, industry players and the general public.

Keywords: Sustainable weed management; Critical period of competition; Herbicide resistance; Weed shift.

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1. Introduction

Southeast Asia (SEA) comprises a diverse group of countries at varying levels of agricultural development and natural resource endowments. The agriculture sector remains to be a major contributor to the development of the national (except for Singapore and Brunei) and regional economy as gleaned from the strong growth in the national gross domestic product of the countries (Organisation for Economic Co-operation and Development, 2017; Bresciani et al., 2019). Farmers are mostly smallholders with farm sizes generally below 5 ha. In Indonesia, Thailand and Philippines, farm sizes have been generally declining. In contrast, Vietnam and Myanmar farm sizes have been increasing due to the government's consolidation efforts across different crop production activities (Organisation for Economic Co-operation and Development, 2017).

Crop production is centered on rice-based systems in most countries and rice cultivation is the main agricultural production activity. In Myanmar, 70% of the rural population engages in rice production for their livelihoods (Connor et al., 2022). In the Philippines, more than 5.5 million households are engaged in agriculture (Philippines Statistical Authority, 2022) and 2.4 million of these are engaged in rice farming (Inter-American Development Bank, 2020). Oil palm production increased in Malaysia since the 1990s and it crowded out rice and vegetables. Recently, Indonesia holds the largest rice production area and volume in the region and it overtook Malaysia as the world's highest palm oil producer. In 2016, the SEA region accounted for 35% and 47% of the values of total rice exports, and 85% and 99% of the values of palm oil exports in the world and in Asia, respectively (Takeshima, Joshi, 2019).

The increasing domestic demand for more and diversified produce and export of agricultural products is driving countries towards highly intensified crop production. This led to changes in farmers' management practices, including increased use of chemical inputs such as fertilizers and pesticides, to boost and stabilize yields and improve production efficiency. In 2010, the amount spent on chemical inputs per hectare of cultivated crop increased by three- to four-folds compared to 1980 and 1990. The volume of herbicides used in Thailand, Philippines, and Myanmar increased steadily from 2015 to 2018 (Food and Agriculture Organization, 2021), indicating the growing reliance on herbicides for weed management. The intensive and continuous use of the same herbicides for a long period of time resulted in a spike of unique cases of herbicide resistance in weeds associated with the staple and perennial crops, posing a serious threat to cost-effective weed management.

Against this backdrop, the purpose of this review is to highlight the history of herbicide use in SEA, the three major cropping systems, and how weed management evolved, including problems associated with injudicious use of herbicides such as herbicide resistance, water pollution and herbicide bioaccumulation in rice field frogs and crabs. We also briefly discuss pesticide regulations and policies and implementation in relation to sustainable herbicide management. Lastly, we propose a framework for sustainable weed management that involves engagement with the various stakeholders in the public and private sectors.

2. History of herbicide use

Herbicides are not modern-day innovations, in fact, chemicals used intentionally on crops for weed control started in the mid-19th century. The first chemicals that were used as herbicides were inorganic salts such as sodium chloride, sodium chlorate, arsenic salts, and copper sulfate for nonselective weed control while inorganic acids such as sulfuric acid and other chemicals (e.g., iron sulfate, dinitros, ammonium sulfate, gasoline, and kerosene) were used for selective control of broadleaved weeds in cereals, legumes, lawns, and vegetable crops (Varanasi, Jugulam, 2017).

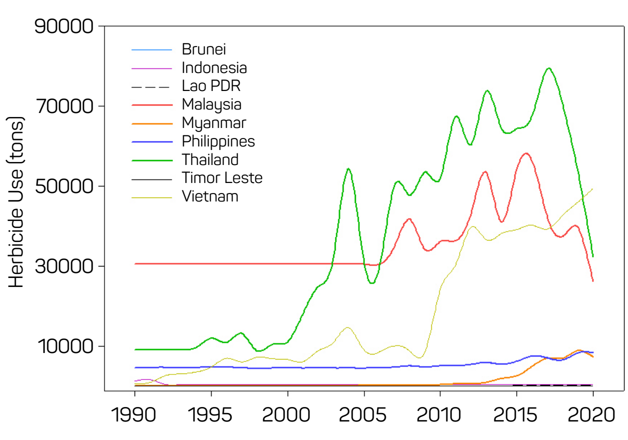
Despite the variable success of the previously mentioned chemicals, research interest in chemical weed control flourished and led to the development of synthetic herbicides. The discovery of phenoxyacetic acids (e.g., 2,4-D and MCPA) in the early 1940s and the chemical processes that allowed for this discovery opened the floodgates for herbicides. By 1950, there were 25 new herbicides in the market for use on different crops and by 1969 a three-fold increase in the number of new herbicide molecules were available for farm, industrial, and landscape use (Timmons, 2005). New chemicals with improved properties, like reduced use rates, and new modes of action (MOA) progressed steadily until about the early 1990s. Since then, development of new herbicides with either a new MOA or novel chemical classes has significantly slowed down.

In SEA, the introduction of herbicides was primarily through agricultural production although the phenoxy herbicide, 2,4,5-T, was mainly used to control woody perennial that became the subject of investigations, particularly because of its use in Vietnam in combination with 2,4-D (2,4-dichlorophenoxy acetic acid) as Agent Orange. Registrations of 2,4,5-T were cancelled, and the product was voluntarily removed by the manufacturers in 1985. The herbicide 2,4-D was initially tested in the Philippines in 1948 to eradicate weeds in lawns and pastures, and subsequently tested for weed control in rice (Mercado, 1979). In the late 1950s, Thailand considered 2,4-D as the only promising herbicide for rice and in the 1960s, it was used in limited rice areas of Malaysia. In Indonesia, however, rice farmers started using MCPA (2-methyl 4-chlorophenoxy acetic acid) to control broadleaved weeds and sedges in 1972 but later switched to 2,4-D in 1978 when the country experienced shortage of MCPA supply (Soekarno, Sandaru, 1982). The 2,4-D herbicide remains among the most useful herbicides developed until today.

Use of herbicides in SEA compared to industrialized countries is significantly lower until today; however, there is a continued demand for herbicides in all countries in the region. Malaysia, Thailand, and Vietnam are the three major users while the rest of the SEA countries have comparatively lower demand. Brunei, Timor Leste, Laos, and Singapore have very few reports documenting their pesticide use (Figure 1). Available information shows that these countries have very low levels of herbicide use (Food and Agriculture Organization, 2022). A summary of the history of herbicide use by country is presented below. It is important to note that herbicide use data can appear as sales and usage data. Sales data are more universal but cannot be directly related to actual use. On the other hand, usage data provide details needed on the actual usage of herbicides; however, they are typically difficult to obtain or are even unavailable for certain crops in an area.

2.1 Cambodia

In Cambodia, the earliest documented report of pesticide application was in the 1990s wherein only 0.7% of farmers used herbicide, while 38.0% and 28.0% used insecticides and rodenticides, respectively (Environmental Justice Foundation, 2002). In 2016, however, the most commonly



Note: No available herbicide use data for Cambodia

Figure 1 - Use of herbicides in Southeast Asia from 1990 to 2020. Source: FAOSTAT (2022); Department of Agriculture (2022); Ministry of Agriculture and Rural Development (2011, 2013); General Statistics Office of Vietnam, 2021

used pesticides were herbicides and insecticides (Flor et al., 2018). Increased use of herbicides was mainly triggered by the mounting difficulty in finding rural workers and the expansion of cultivated land areas. Cassava, corn, and rice farmers are the most prominent users of herbicides. In addition, provinces with intensive rice cropping systems had higher herbicide use with as much as nine applications per season (Flor et al., 2018).

Cambodia does not manufacture pesticides, but imports them from Thailand, Vietnam, and China. In 2001, 111 tons of herbicides were imported but in 2004, the import declined to 54 tons corresponding to 51.0% less from 2001 (Knoema, 2022). At present, about 30 herbicide active ingredients are permitted for agricultural use in the country.

2.2 Indonesia

Herbicides are widely used in Indonesia, although usually supplemented with mechanical and hand weeding, especially in tropical fruit and sugarcane production. In the 1970s, progressive farmers in some parts of the country began to apply MCPA in rubber, oil palms, coffee, and rice fields (Sundaru, 1981). After more than a year of use, farmers switched to 2,4-D as MCPA disappeared in the market. By the 1980s, 25 active ingredients were registered for food crops. Farmers started using oxadiazon, paraquat, propanil, bentazon, pretilachlor, ametryn, and premixes such as bentazon plus 2,4-D, piperophos plus 2,4-D, and thiobencarb plus propanil in rice (Soekarno, Sundaru, 1982). During the fallow period, glyphosate was used to kill weeds before broadcasting rice. Atrazine, alachlor, linuron, chlorbromuron, metribuzin, and difenamide were also used in corn, soybean, and potato (Soekarno, Sundaru, 1982). Glyphosate accounted for 73% of the total herbicide active ingredient used for agricultural crops. Of these crops, oil palm was applied the most which accounted for nearly two-thirds of the total glyphosate use in the country. Other crops in which glyphosate is intensively used are rice, corn, rubber, and non-crop areas (roadsides, parks, waterways, and other land put to uses other than agriculture). Usage in rice and corn is usually single application as part of land preparation, while in rubber and non-crop use, glyphosate is commonly applied 2 to 3 times per year (Brookes, 2019). Detailed information on pesticide use in the country is limited, though between 2000 and 2019, annual herbicide use on agricultural crops remained stable at around 354 tons (Food and Agriculture Organization, 2022).

2.3 Malaysia

Malaysia is the top user of herbicides among SEA countries. Herbicides accounted for about 80% of the total pesticide usage in the country. According to Food and Agriculture Organization (2022), about 34,084 and 56,430 tons of herbicide active ingredients were used in Malaysia during 2006 and 2016, respectively. This represented an annual average growth rate of 6.56% over the past 10 years. Rice, oil palm, and rubber are the major crops that have high dependency on herbicides due to their monoculture production system. Active ingredients such as paraquat, glufosinate, glyphosate, fluazifop, metsulfuron, and triclopyr are commonly used in oil palm and rubber plantations while 2,4-D, bensulfuron, pyrazosulfuron, propanil, quinclorac, and cyhalofop-butyl are intensively used in rice (Dilipkumar et al., 2017).

2.4 Myanmar

Myanmar is the second largest country in the SEA, where 60% of its population directly or indirectly depends on agricultural activities for livelihood. Myanmar is similar with Thailand with regards to crops planted, cultivation patterns, and weather conditions; however, pesticide use is comparatively lower. Traditionally, agriculture in this country has involved little use of pesticides but in the past two decades a considerable increase in imports of pesticides from China has occurred. From 2004 to 2014, pesticide importation varied from 1,000 to 6,000 tons, whereas after 2015 importation stabilized at more than 10,000 tons. Volume and percentage of herbicides readily increased while that of insecticide decreased thereafter. Herbicide use in Myanmar increased from 38 tons in 2000 to 9,740 tons in 2019 growing at an average rate of 41.24% per year (Food and Agriculture Organization, 2022). As of 2019, there are roughly 20 active ingredients commercially available to farmers with glyphosate, 2,4-D amine, pretilachlor, fomesafen, and quinclorac as the most sold, summing up to about 900 metric tons imported per year.

2.5 Philippines

Similar to Indonesia, herbicides are widely used for weed control, though commonly as a supplementary form of weed control to mechanical and hand weeding. Use of herbicides in the country dates back in 1948 when 2,4-D was introduced for control of broadleaved weeds. The use of 2,4-D marked the beginning of selective chemical control paving the way to the gradual herbicide use in the late 1950s (Capinpin, 1975). In the 1960s and 1970s, amides (butachlor and propanil) and thiocarbamates (thiobencarb) were introduced and promptly accepted by rice farmers because of the ability of these herbicides to provide pre-emergence grass control (Datta, Bernasor, 1973). Oxadiazon, pretilachlor, bentazon, and pendimethalin were also introduced for weed control in rice and other crops in the 1970s and 1980s (Cruz, 1990). Triazines (atrazine, simazine, and ametryn), ureas (diuron and monuron), uracils (bromacil and terbacil), and bipyridinium (paraquat) were introduced for weed control in plantation and field crops like pineapple, sugarcane, and banana in the 1960s and 1970s and are still frequently used today (Capinpin, 1975). Fenoxaprop and cyhalofop were introduced in the 1980s and 1990s for postemergence grass and broadleaved weed control (Baltazar et al., 1993; Datta, Baltazar, 1996) but were not fully utilized until the 2000s. Sulfonylureas (bensulfuron, ethoxysulfuron, imazosulfuron, and cyclosulfamuron) were introduced in the 1990s for postemergence control of broadleaved weeds and sedges in rice. In late 1990s and early 2000s, penoxsulam, pyribenzoxim, carfentrazone, clomazone, and bispyribac-sodium were registered and utilized in rice weed management (Cruz et al., 2002).

As of 2021, there are 55 herbicide active ingredients (either solo or premix) registered in the Philippines (Fertilizer and Pesticides Authority, 2022). Glyphosate accounts for 48% of the total active ingredient used. The main glyphosate user crops are corn and plantation crops, although this is also used in non-crop areas and as no-till preplant treatments in annual crops. In rice production, butachlor, propanil, pretilachlor, 2,4-D, bispyribac-sodium, and cyhalofop-butyl are commonly used for control of broadleaved weeds and grasses. On average, the country imports 10,000 tons of herbicides annually (Fertilizer and Pesticide Authority, 2021).

2.6 Thailand

Thailand relies heavily on herbicide use as a tool for crop protection to intensify crop production. According to the Office of the Agriculture Regulation (OAR) of the Department of Agriculture, about 80% of annual pesticide imports are herbicides. In 2000, importation was less than 20,000 tons but increased to approximately 55,000 tons in 2004, to about 68,000 tons in 2011 (Department of Agriculture, 2021). Application of herbicides has also increased about two-fold from 2005 to 2018 with an average usage of 1.3 to 2.9 kg a.i. per one ha of cropland. The top three herbicide imports to Thailand are 2,4-D, glyphosate, and glufosinate, with 11,781, 7,240, and 3,194 tons imported in 2021, respectively (Department of Agriculture, 2021). These three herbicides account for 67% of all herbicide imports in the country. Other most imported herbicides are butachlor, acetochlor, atrazine, pendimethalin, diuron, and ametryn (Panuwet et al., 2012; Laohaudomchok et al., 2021).

2.7 Vietnam

Herbicides are widely used for weed control in Vietnam, though commonly as a secondary or supplementary form of weed control to mechanical and hand weeding (Brookes, 2019). Use of herbicides for control of weeds started in the 1970s with the introduction of 2,4-D, propanil, and pentachlorophenol for use in rice (Chin, 2001). In the 1980s, only a handful types of herbicides were additionally introduced, mostly of which were for spring crops. However, the trend of herbicide use began to increase in the 1990s. In 1991, herbicide application in the country was about 900 tons but in the mid-1990s, quantities used increased to 3,600 tons (Food and Agriculture Organization, 2022) to near 11,000 tons in 2003 (Ministry of Agriculture and Rural Development, 2011), and to about 50,000 tons in 2020 (General Statistics Office of Vietnam, 2021). In 2019, the Ministry of Agriculture and Rural Development (MARD) published a list of 503 active ingredients allowed for use in agriculture of which 85 were herbicides mostly for rice. Most commonly used active ingredients in rice are thiobencarb, quinclorac, bispyribac-sodium, butachlor, pyrazosulfuron-ethyl, oxadiazon, pretilachlor, propanil, 2,4-D, ethoxysulfuron, cyhalofop-butyl, bensulfuron-methyl, and acetochlor (Chin, 2001; Thanh, Tran, 2020). In plantation crops, glyphosate is the most commonly used with 2 to 3 applications per season for land preparation and in-between crop weed control, accounting for 36% of the total herbicide use in the country (Brookes, 2019). Glyphosate, along with paraquat and 2,4-D, are considered as highly hazardous pesticides and thus are listed as banned herbicides in Vietnam (Ministry of Agriculture and Rural Development, 2022; Thanh, Tran, 2020).

3. Overview of cropping systems and herbicide use

The region has a tropical climate making it suitable for field crop production during most parts of the year. In non-irrigated areas, cropping patterns are determined primarily by the duration and amount of rainfall, with most of the area subject to a monsoon climate (Harwood, Price, 1977). Cropping pattern alternatives and the number of possible sequential crops per year are numerous. However, the cropping system and the level of cropping intensification and diversification are affected by factors such as natural resource endowments particularly water supply, market demand, proximity to market, and skills of the farmers to grow the crops. In recent years, the trajectory of crop intensification is towards larger production of single crops such as rice in Cambodia and palm oil in Malaysia, Indonesia and Thailand. In smallholder farms, diversification through multiple cropping continues to prevail.

The area under multiple cropping systems in SEA accounts for 13.28 M ha (Waha et al., 2020). Regardless of cropping systems, crop production is challenged by decreasing natural resources, increasing cost of production, and abiotic and biotic stresses such as insect pests, diseases and weeds. Weeds cause significant yield reduction and economic losses if left uncontrolled. Weed management will become more challenging with the spikes in herbicide resistance in weeds and with climate change impacting weed population and crop management in the future. Efforts to reduce yield losses through the adoption of integrated weed management, including herbicide use, bring tremendous opportunities to improve and stabilize farm productivity in the region.

3.1 Rice-based cropping system

Rice-based cropping systems are common during the rainy season with follow on crops during the dry season especially in areas with a rainy season long enough to support cultivation of two to three crops in a year. The gradual or rapid onset, or decline, of heavy rains determines the type of culture of rice, which crops should be used as second or main crop in the pattern, and relative degree of difficulty of tillage (Harwood, Price, 1977). Rice-based patterns require an annual rainfall of 1500 mm or more and at least 200 mm/month rainfall for three consecutive months. In Vietnam, the world's fifth largest rice producer, the dominant cropping patterns are rice-rice, rice-cash crop, rice-maize, and rice-aquaculture (Kien et al., 2014; Global Yield Gap Atlas, 2020). Double or triple rice cropping in a year and double season rice are common in the Mekong and Red River Deltas, respectively (Global Yield Gap Atlas, 2020).

Rice-rice cropping pattern in a year is dominant in fully irrigated areas in SEA but diversification of non-rice crops is also encouraged to raise farm incomes and intensify employment opportunities in the rural areas. The rice crop is established either as transplanted or direct-seeded. Direct seeding is increasingly becoming popular because it is more rapid and easy to sow, less labor intensive, reduces water use and has lesser methane emission (Yadav et al., 2021). However, weeds and rice emerge and grow almost simultaneously and the suppressing effect of standing water on weed growth at crop emergence is absent. Thus, the magnitude of the weed problem in this system is greater than in transplanted rice. The wide adoption of direct-seeded rice systems has led to the increase in weedy rice infestation in rice fields (Chauhan, 2013). Upland crops grown after rice are also transplanted or direct-seeded, mostly in a dry field. The magnitude of the weed problem is also higher in direct-seeded crops because of the absence of size differential between the crop and the weeds.

Weeds associated with rice production during the monsoon season are quite distinct from those that grow with other upland crops in summer season. *Echinochloa* species, weedy rice, and several *Cyperus* species continue to dominate the weed complex in lowland rice (Kraehmer et al., 2016). However, weeds are showing adaptation to changes in cropping systems and limited availability of water. Purple nutsedge (*Cyperus rotundus* L.), a dominant weed in the upland crop after rice is now observed in monsoon rainfed rice and in irrigated rice fields (Donayre et al., 2015). Weedy rice is currently a major problem in direct seeded rice areas in the region. There have also been reports in Malaysia that weedy rice has developed resistance to imidazolinone in rice fields planted with Clearfield rice (Jaafar et al., 2014).

Regardless of the crop, effective weed management is important to avoid yield losses due to weeds. Various options are available to manage weeds in rice and other crops. Indirect control options include the use of clean, weed-free seeds, tilling and land preparation, water management, competitive cultivars, and crop rotation. Direct control methods include manual weeding and use of herbicides (Azmi et al., 2012; Paiman et al., 2020).

Herbicide use in rice is quite prevalent, especially in direct-seeded rice and its use has been increasing, owing to high labor costs (Beltran et al., 2012; Juliano et al., 2020) and declining availability of agricultural labor (Martin et al., 2021). There are numerous herbicides commonly used in rice (Karim et al., 2004; Donayre et al., 2019) and these are discussed extensively in the preceding section. Some of these are continuously used by farmers over long periods resulting in herbicide resistance in *Echinochloa crus-galli* P. Beauv in the Philippines (Juliano et al., 2010) and in other SEA countries (Kumar et al., 2017). The excessive use of herbicides in rice also resulted in the contamination of surface water and groundwater in Thailand. Some of the herbicides detected include atrazine and 2,4-D (Thapinta, Hudak, 2003), paraquat and glyphosate (Noicharoen et al., 2012; Anlauf et al., 2018). Bioaccumulation of herbicides in edible aquatic animals such as rice field frogs and crabs pose potential risk to people as these are consumed as food in the rural areas. High levels of atrazine and paraquat were found in the rice frogs in fields with intensive herbicide use compared to unsprayed fields while rice field crabs were found to contain high levels of paraquat in their meat (Laohaudomchok et al., 2021).

3.2 Corn-based cropping system

Corn-based cropping systems are common in the upland plains and rolling to hilly areas in the Philippines (Gerpacio et al., 2004), Vietnam, northern Laos, and Indonesia (GYGA, 2020). Bulk of the corn production occurs during the monsoon season. However, in some areas, such as in Luzon and Mindanao islands of the Philippines, where the rainfall is more or less equally distributed during the year, two to three corn crops can be planted in one year (Gerpacio et al., 2004; Salazar et al., 2021). In other locations where there is sufficient rainfall for another crop, short maturing legumes and vegetables are planted after corn.

The corn-based cropping systems are as important as the rice-based cropping systems as these provide the basic staple for consumption in sub-Saharan Africa, Central America, the Andean region, and much of the poorer parts of Asia. They also provide fodder for the livestock systems in many countries (Falcon, Naylor, 1998). In SEA, the major corn producing countries include Indonesia, Philippines, Vietnam, and Thailand (Witt et al., 2006).

A complex of grass, broadleaved, and sedge weeds invade corn-based fields even before the crops germinate. Potential yield losses in corn due to weeds range from 16 to 80%, but Paller et al. (2003) indicated an actual yield loss of 44 to 60%. Traditionally, mechanical inter row cultivation and manual hand weeding are the predominant weed management practices of farmers in the region. However, due to shortage and increasing cost in farm labor, farmers had become reliant on herbicides to control weeds. With the development of herbicide resistant corn, glyphosate usage surged in the Philippines, Thailand, Indonesia, and Vietnam (Brookes, 2019).

3.3 Perennial crop-based cropping system

Oil palm and coconut are important economic crops in SEA. Indonesia and the Philippines, together with India, rank as the top three coconut producers in the world (Arulandoo et al., 2017). Indonesia, Malaysia, and Thailand are also the top three producers of palm oil globally. These are cultivated on a large scale in both plantations and smallholdings for food and nonfood industrial purposes. In plantations, these crops are commonly grown as monocrop while in the smallholdings, particularly coconut, other timber and fruit tree species and cash crops are integrated. This multi-storey coconut-based cropping system allows the cultivation of diverse crop species of varying heights on the same piece of land thus using water, land and space in a most efficient and economical manner (Jalani et al., 2003; Singh et al., 2008).

Weeds are an important constraint in perennial crop-based cropping systems especially during the early years of crop establishment. As canopies of the trees close in, the magnitude of the weed problem is substantially reduced.

In oil palm plantations, weeds such as *Tetracera indica* (Houtt. ex Christm. & Panz), *Lantana camara* L., *Solanum torvum* Sw., *Dieffenbachia* sp., *Typhonium flagelliforme (G. Lodd.) Blume* and *Stenoclaena palustris* (Burm.f.) Bedd. are difficult to control and the use of chemical control alone cannot provide sufficient level of control. Woody weed species such as the *Chromolaena odorata* (L) R.M.King & H.Rob., *Oldenlandia verticillata* L., and *Melastoma malabathricum* L., and the creeping *Mikania micrantha* Kunth are particularly difficult to control and can decrease the palm fruit production (Ruzlan, Hamdani, 2021).

Majority of oil palm companies in Malaysia and Indonesia rely on herbicides to control weeds (Ruzlan, Hamdani, 2021; Purba and Sipayung, 2022). Glyphosate has been used in oil palm for four decades. This intensive use of glyphosate led to the development of herbicide resistant populations of *Eleusine indica* (Linn.) Gaertn in oil palm plantations in Sumatra, Indonesia (Purba and Sipayung, 2022). This development calls for more prudent weed management strategies to prevent more weeds from developing herbicide resistance.

Various weed control practices, including chemical, cultural, mechanical, and biological, are available to manage weeds in oil palm. Typical practices include herbicide application (e.g., paraquat, glyphosate isopropylamine, metsulfuron-methyl, and triclopyr) and hand weeding, slashing of woody weeds, cover cropping, mulching, and managing planting density. Livestock grazing is the main method for biological control. The combination of management practices varies depending on the growth stage of the crops. In a survey conducted by Ruzlan, Hamdani (2021), more plantations are implementing integrated weed management and shifting away from heavy reliance on herbicides; 70% of the 60 respondents used a combination of herbicide application, cultural management, and biological control methods while 30% used chemical control alone.

4. Challenges for sustainability of herbicide use

The use of herbicides in many crops and cropping systems contributes greatly to reducing the impact of weeds on yield. Its contribution in easing constraints such as shortage of labor and environmental concerns such as sustainable use of water cannot be denied. As many countries move from traditional farming methods to use of technologies, herbicide use becomes an important component of efficient crop production. The challenge to most farmers in SEA is the continuous and sustainable use of these herbicides.

4.1 Herbicides as a component of an integrated weed management (IWM) system

IWM entails the use of all available compatible control tactics to minimize yield losses. The current weed management in agricultural systems is characterized by the widespread use of either chemical, physical, mechanical, and or cultural methods. In addition, non-conventional weed control strategies such as mulching, cover crops, soil solarization, thermal weed control, and biological control through livestock grazing are also used to control weeds (Scavo, Mauromicale, 2020). A lot of farmers are reluctant to adopt IWM practices due to the convenience of using herbicides alone. Furthermore, most farmers find IWM complex, time-consuming, and costly (Moss, 2019).

An integrated approach in weed management is necessary if long-term effective control of weeds is desired. Using a single tactic over long periods of time is without any consequence and may not be enough to counter the impact of a dynamic weed population in the field. Changes in weed composition may occur regardless of the tactic used, while herbicide resistant weeds may dominate the weed spectrum as a consequence of overreliance on a single MOA of herbicides (Karim et al., 2004). Herbicide as a component of an integrated weed management system would mean recognizing that in certain situations, herbicide can be the first rather than last option. Newly introduced weeds that would require immediate eradication before they spread to other areas can be controlled with the use of herbicide. Additionally, herbicides can also be the only option after cultural or physical control tactics have been employed and for certain considerations important to the economics of farming such as the case of direct-seeding in rice. In the Philippines, the shift from transplanting to direct-seeding in rice was due to many economic as well as environmental factors (Marsh et al., 2009). A closer analysis of the prevailing weed management practices by farmers revealed that there was overreliance on herbicides as the cost-effectiveness of other control tactics are in question. Combining cultural management practice, judicious use of intermittent irrigation and minimal herbicide use resulted in higher yields of about 10% and 15% in Nueva Ecija and Iloilo provinces, respectively (Marsh et al., 2009).

Another example, the majority of rice farmers in Northwest Cambodia use a narrow range of herbicides to control weeds. In 2008-2009, farmers used herbicides but heavily relied on using 2,4-D. In 2017, 76% of the rice farmers who practice DSR in Northwest Cambodia still use 2,4-D but farmers started to diversify the herbicides they use. By 2018-2019, 100% of the farmers use herbicides and a drastic increase in the usage of other herbicide active ingredients such as bispyribac-sodium and fenoxaprop + pyrazosulfuron + quinclorac was observed (Martin et al., 2021). Some of the farmers practice hand weeding in combination with herbicide application but the farmers only use post-emergence herbicides.

4.2 Development of herbicide resistance in weed populations

Resistance in weeds is a consequence of their adaptive evolution to intense selection pressure exerted by continuous applications of herbicides (Powles, Yu, 2010). Two types of mechanisms are involved in herbicide resistance (HR): (F1) target-site resistance caused by structural alterations or increased activity of the herbicide target protein; and (2) non-target site resistance caused by reduced herbicide uptake or translocation or enhanced herbicide metabolism (Délye, 2013; Powles, Yu, 2010). Metabolism-based HR due to the enhanced activity of endogenous plant enzymes such as cytochrome P450 monooxygenases, glycosyl transferases, glutathione S-transferases, etc. confer resistance to herbicides of different chemical groups and MOAs (Yu, Powles, 2014), thus leading to cross-resistance cases.

Prevalence of herbicide-resistant weeds in many cropping situations is a global concern. Currently there are 512 unique cases involving 266 weed species and 21 herbicide sites of action in 96 crops and 71 countries (Heap, 2022). In SEA, there are 37 unique cases involving 17 weed species and 30 active ingredients. Malaysia tops the list with 20 cases followed by Thailand, Indonesia and Philippines at 7, 5, and 3 cases, respectively (Heap, 2022). The Philippines was the earliest to document HR in 1983 involving *Sphenoclea zeylanica* Gaertn. with 2,4-D. A second case for the country was reported after 22 years in barnyardgrass (*E.crus-galli* var *crus-galli*) involving butachlor and propanil. Both of these cases were in rice. In contrast, Malaysia's HR cases varied by active ingredients, weed species and crops. Among the active ingredients, paraquat resistance has been reported in 8 cases. Malaysia also has the highest number of multiple and cross resistance issues (Table 1).

While these are documented cases based solely on the International Herbicide Resistance Database, the possibility of more cases of HR cannot be denied. The chances of herbicide resistance happening in other SEA countries are not remote. In the Philippines alone, suspected cases of HR in weeds in corn is common knowledge among farmers who have been observing reduced control with the use of glyphosate in genetically modified (GM) corn. However, there are no studies being conducted to confirm such suspicion.

The occurrence of herbicide resistance in weed populations presents a big challenge as it limits the herbicide choices for effective weed management. This results in significant increase in yield reduction due to weeds and renders the herbicide to which herbicide resistance has been reported seemingly useless. It affects the cost-effectiveness of a weed control program, as farmers are forced to rely on mechanical control which entails labor costs.

4.3 4.3. Environmental impacts of herbicide use

Environmental impacts due to widespread use of agricultural chemicals has been one of the major concerns. Groundwater contamination, residues on crops and food products and effects on conservation of biodiversity are among the many ways herbicides are able to affect the environment. In a recent review of the journal articles on emerging contaminants in SEA revealed that pesticides were second to pharmaceutical compounds. Among the pesticides, atrazine, glyphosate and paraquat have been identified as emerging contaminants, with atrazine concentrations being reported as way below the standards (Lee et al., 2022). Meanwhile, atrazine and 2,4-D were detected in surface and groundwater samples in Thailand indicating groundwater contamination (Laohaudomchok et al., 2021).

Additionally, soil and biota herbicide contamination were also found in many regions of Thailand. Bioaccumulation of high levels of herbicides such as atrazine and paraquat in edible plants, rice field crab meat and rice frog have also been reported in Thailand. In 2020, the Thailand Pesticide Alert Network (Thai-PAN) detected the presence of pesticide residues in fresh oranges sold in Thailand markets (Lauhaudomchok et al., 2021).

As the demand for food increases, there is consequent expansion of areas for production. As such, areas near biodiversity hotspots are not spared from non-target movement of herbicides contributing to loss of biodiversity. For example, glyphosate and 2,4-D have been key herbicides in controlling weeds of tea and coffee plantations in the region. Incidentally, these plantations are near protected areas hence there is contamination

Table 1 - Herbicide resistance cases in Southeast Asia (Heap, 2022)

Country	Year Reported	Weed	Mode of Action	Active Ingredient	Situations	References
Indonesia	1995	*Limnocharis flava*	Auxin Mimics HRAC Group 4 (Legacy O)	2,4-D	Rice	Heap, 2022
	2012	*Eleusine indica*	Inhibition of Enolpyruvyl Shikimate Phosphate Synthase HRAC Group 9 (Legacy G), PS I Electron Diversion HRAC Group 22 (Legacy D)	glyphosate, paraquat	Oil Palm Nursery	Heap, 2022
	2012	*Eleusine indica*	PS I Electron Diversion HRAC Group 22 (Legacy D)	paraquat	Corn (maize)	Heap, 2022
	2019	*Eleusine indica*	Inhibition of Enolpyruvyl Shikimate Phosphate Synthase HRAC Group 9 (Legacy G)	glyphosate	Oil Palm Plantation	Tampubolon et al., 2019
	2022	*Monochoria vaginalis*	Inhibition of Acetolactate Synthase HRAC Group 2 (Legacy B)	bensulfuron-methyl, bispyribac-sodium, and penoxsulam	Rice	Widianto et al., 2022
Malaysia	1989	*Fimbristylis miliacea*	Auxin Mimics HRAC Group 4 (Legacy O)	2,4-D	Rice	Heap, 2022
	1989	*Ischaemum rugosum*	PS I Electron Diversion HRAC Group 22 (Legacy D)	paraquat	Vegetable, Rubber	Heap, 2022
	1990	*Eleusine indica*	PS I Electron Diversion HRAC Group 22 (Legacy D)	paraquat	Vegetables	Heap, 2022
	1990	*Eleusine indica*	Inhibition of Acetyl-CoA Carboxylase HRAC Group 1 (Legacy A)	fluazifop-butyl, propaquizafop	Cropland, Vegetables	Heap, 2022
	1990	*Solanum nigrum*	PS I Electron Diversion HRAC Group 22 (Legacy D)	paraquat	Vegetables	Heap, 2022
	1990	*Crassocephalum crepidioides*	PS I Electron Diversion HRAC Group 22 (Legacy D)	paraquat	Vegetables	Heap, 2022
	1990	*Amaranthus blitum* (ssp. *oleraceus*)	PS I Electron Diversion HRAC Group 22 (Legacy D)	paraquat	Vegetables	Heap, 2022
	1990	*Conyza sumatrensis*	PS I Electron Diversion HRAC Group 22 (Legacy D)	paraquat	Vegetables	Heap, 2022
	1995	*Sphenoclea zeylanica*	Auxin Mimics HRAC Group 4 (Legacy O)	2,4-D	Rice	Heap, 2022
	1997	*Eleusine indica*	Inhibition of Acetyl-CoA Carboxylase HRAC Group 1 (Legacy A), Inhibition of Enolpyruvyl Shikimate Phosphate Synthase HRAC Group 9 (Legacy G)	fluazifop-butyl, glyphosate	Orchards	Heap, 2022
	1998	*Limnocharis flava*	Auxin Mimics HRAC Group 4 (Legacy O), Inhibition of Acetolactate Synthase HRAC Group 2 (Legacy B)	2,4-D, bensulfuron-methyl	Rice	Heap, 2022
	2000	*Sagittaria guyanensis*	Inhibition of Acetolactate Synthase HRAC Group 2 (Legacy B)	bensulfuron-methyl	Rice	Heap, 2022
	2000	*Bacopa rotundifolia*	Inhibition of Acetolactate Synthase HRAC Group 2 (Legacy B)	bensulfuron-methyl, pyrazosulfuron-ethyl, metsulfuron-methyl	Rice	Heap, 2022

Continue

Continuation

Country	Year Reported	Weed	Mode of Action	Active Ingredient	Situations	References
Malaysia	2002	*Limnophila erecta*	Auxin Mimics HRAC Group 4 (Legacy O), Inhibition of Acetolactate Synthase HRAC Group 2 (Legacy B)	2,4-D, bensulfuron-methyl, cinosulfuron, pyrazosulfuron-ethyl, mesosulfuron-methyl	Rice	Heap, 2022
	2005	*Hedyotis verticillata*	Inhibition of Enolpyruvyl Shikimate Phosphate Synthase HRAC Group 9 (Legacy G), PS I Electron Diversion HRAC Group 22 (Legacy D)	glyphosate, paraquat	Palm oil	Heap, 2022
	2006	*Leptochloa chinensis*	PSII inhibitors - Serine 264 Binders HRAC Group 5 (Legacy C1 C2)	propanil	Rice	Heap, 2022
	2009	*Eleusine indica*	Inhibition of Glutamine Synthetase HRAC Group 10 (Legacy H), PS I Electron Diversion HRAC Group 22 (Legacy D)	glufosinate-ammonium, paraquat	Vegetables	Heap 2022
	2009	*Eleusine indica*	Inhibition of Acetyl-CoA Carboxylase HRAC Group 1 (Legacy A), Inhibition of Enolpyruvyl Shikimate Phosphate Synthase HRAC Group 9 (Legacy G), Inhibition of Glutamine Synthetase HRAC Group 10 (Legacy H), PS I Electron Diversion HRAC Group 22 (Legacy D)	haloxyfop-methyl, fluazifop-butyl, butroxydim, glyphosate, glufosinate-ammonium, paraquat	Oil Palm Nursery	Heap, 2022
	2010	*Clidemia hirta*	Inhibition of Acetolactate Synthase HRAC Group 2 (Legacy B)	metsulfuron-methyl	Palm oil	Heap, 2022
	2018, 2020	*Oryza sativa var. sylvatica*	Inhibition of Acetolactate Synthase HRAC Group 2 (Legacy B)	imazapyr, imazapic	Rice	Heap, 2022, Ruzmi et al., 2020
Philippines	1983	*Sphenoclea zeylanica*	Auxin Mimics HRAC Group 4 (Legacy O)	2,4-D	Rice	Heap, 2022
	2005	*Echinochloa crus-galli* var. *crus-galli*	PSII inhibitors - Serine 264 Binders HRAC Group 5 (Legacy C1 C2), Very Long-Chain Fatty Acid Synthesis inhibitors HRAC Group 15 (Legacy K3 N)	propanil, butachlor	Rice	Heap, 2022
	2017	*Eleusine indica*	Inhibition of Enolpyruvyl Shikimate Phosphate Synthase HRAC Group 9 (Legacy G)	glyphosate	Non-crop	Kaundun et al., 2008
Thailand	1998	*Echinochloa crus-galli* var. *crus-galli*	PSII inhibitors - Serine 264 Binders HRAC Group 5 (Legacy C1 C2), Very Long-Chain Fatty Acid Synthesis inhibitors HRAC Group 15 (Legacy K3 N)	propanil, butachlor	Rice	Heap, 2022
	2000	*Sphenoclea zeylanica*	Auxin Mimics HRAC Group 4 (Legacy O)	2,4-D	Rice	Heap, 2022
	2001	*Echinochloa ruz-galli* var. *ruz-galli*	Inhibition of Acetyl CoA Carboxylase HRAC Group 1 (Legacy A)	cyhalofop-butyl, quizalofop-ethyl, fenoxaprop-ethyl	Rice	Heap, 2022

Continue

Continuation

Country	Year Reported	Weed	Mode of Action	Active Ingredient	Situations	References
Thailand	2002	*Leptochloa chinensis*	Inhibition of Acetyl CoA Carboxylase HRAC Group 1 (Legacy A)	quizalofop-ethyl, fenoxaprop-ethyl, profoxydim	Rice	Heap, 2022
	2021	*Eleusine indica*	Inhibition of Acetyl-CoA Carboxylase HRAC Group 1 (Legacy A)	fenoxaprop-P-ethyl, fluazifop-P-butyl, haloxyfop-R-methyl, propaquizafop, and quizalofop- P-tefuryl	Vegetables	Pinsupa et al., 2021
	2022	*Fimbristylis miliacea*	Inhibition of Acetolactate Synthase – HRAC GROUP 2 (Legacy B)	penoxsulam, bispyribac-sodium, pyribenzoxim and pyrazosulfuron-ethyl	Rice	Rachsapa et al., 2022
	2022	*Echinochloa crus-galli* var. *crus-galli*	Auxin Mimics HRAC Group 4 (Legacy O)	quinclorac	Rice	Pinsupa et al., 2022
Vietnam	2017	*Echinochloa crus-galli* var. *crus-galli*	Inhibition of Acetolactate Synthase HRAC Group 2 (Legacy B), Inhibition of Cellulose Synthesis HRAC Group 29 (Legacy L)	bispyribac-sodium, penoxsulam, quinclorac (MOA in monocots)	Rice	Heap, 2022
	2022	*Echinochloa ruz-galli* var. *ruz-galli*	Inhibition of Very Long-Chain Fatty Acid Synthesis inhibitors – HRAC GROUP 15 (Legacy K3 N)	pretilachlor	Rice	Thuy et al., 2022

Most of the data are adopted from Heap, I. The International Herbicide-Resistant Weed Database. Online. Tuesday, April 12, 2022. Available www.weedscience.org.

of these herbicides that pose threat to conservation of biodiversity (Gupta, 2012).

Environmental contamination and residues in food products creates substantial doubts on the utility of herbicides in agricultural production as this poses risk to human health. It is tough to choose between supporting lives through increased food production and opting to use agricultural products that are deemed unsafe to human health to boost agricultural productivity.

4.4 Lack of farmer education on judicious use of herbicides

Knowledge, attitude and behavior of farmers play a vital role in the safe and judicious use of herbicides. Judicious use of herbicides calls for safe, efficient and proper use of commercially available formulations that are registered for the intended crop and in the country. Thorough understanding of the risk associated with use of agrochemicals, consequences of unsafe practices such as eating and smoking during and after application, use of proper personal protective equipment (PPE), the need for proper hygiene and use of well calibrated spraying equipment are important considerations. There is a direct relationship between sufficient knowledge on the proper use, handling, storage and disposal of agricultural chemicals and low occurrences of health-related incidents (Matthews, 2008). Exposure of farmers and children to herbicides due to its improper use resulted in health problems. In the Philippines, reports of health hazards such as poisoning, blindness, and nail erosion associated with paraquat were documented (Quijano et al., 2017) while in Vietnam, children exposed to herbicides and other pesticides were reported to experience dizziness, vomiting or nausea, headache and difficulty of breathing (Pesticide Action Network Asia and in the Pacific, 2020). Efficient and proper use of herbicides calls for the proper timing of application of the correct dose for the target weed to effectively control weeds and avoid adverse effects on human health and the environment.

All countries have existing agriculture extension systems and networks mandated to support farmers, including provision of training opportunities on various aspects of crop production and management (Damalas, Koutroubas, 2017). Farmer education is necessary to ensure that herbicides are used properly. Knowledge on the MOA, application timings, and herbicide mixtures is imperative to maximize the use of herbicide technology in any production systems. In many SEA countries, misuse stems from the fact that farmers do not fully understand how herbicides work and how they can use it to their advantage in managing weed problems (Sharifzadeh, Abdollazadeh, 2021). In Cambodia and Lao PDR, problems on proper use of herbicides are common as labels are written in the language of the country where the herbicide was imported from. Oftentimes farmers do not understand the information contained in the label (Vazquez et al., 2013).

4.5 Lenient implementation of regulations and policy towards herbicide use

Local authorities and government organizations which manage and control pesticide use are present in all SEA countries and all of them adhere to the FAO Code of Conduct for pesticide management. Despite following the FAO Code of Conduct for Pesticide Management, countries like Vietnam and Indonesia have the least legal measures on managing pesticide use (Mohammad et al., 2018).

There is a need to strengthen pesticide regulations most especially on herbicides. Among the SEA countries, the Philippines leads in terms of regulation with the establishment of the Fertilizer and Pesticide Authority (FPA). FPA is responsible for registration of new chemical formulations and monitoring of registered pesticide products. Such governing entities are not always present in SEA countries. In contiguous countries that share borders, such as Cambodia and Laos PDR, illegal pesticide trade has been documented (Vazquez et al. 2013). These studies show similar broad problems on pesticide regulation and illegal entry of unregulated herbicides in Vietnam, Thailand, and Myanmar. In Myanmar, for example, agricultural supply stores sell herbicides originating from neighboring countries that have not gone through herbicide testing and registration procedures (Annamalai et al., 2021). Myanmar has an existing pesticide law and other associated policies but lenient implementation of the rules and regulations is pervasive. In Malaysia, several reports have been published on the presence of illegal pesticides which were brought by farmers from neighboring countries where its prices are cheaper. These illegal pesticides are being traded despite the existence of the Pesticides Act of 1974 which regulates all pesticides and other chemicals used in agriculture (Rahman, 2021).

The advancement of pesticide management in SEA started in the past decade. FAO's goal was to harmonize the pesticide regulatory processes and guidelines in SEA countries. Different countries have started reviewing and improving their pesticide management system. In Bangladesh, the number of required efficacy trials for pesticides has been increased. Various hazardous pesticides have been restricted in Myanmar. Meanwhile, Sri Lanka and Thailand have introduced new registration procedures and requirements. In the Philippines, the National Single Window (NSW) system has been implemented to facilitate the pesticide trading system in the country. The NSW system allows parties to submit their import, export, and transit-related requirements online which eases the application and registration process involved in trading (FAO, 2013).

5. Perspective on sustainable weed management

Unsustainable weed management leads to various problems such as economic losses, shifts in weed flora, development of herbicide resistance, and adverse effects to the environment. The integrated weed management approach combining direct and indirect control methods and based on the critical period of crop-weed competition renders sustainable methods to overcome weed problems while reducing the costs to farmers and minimizing harm to the environment. A more inclusive weed management strategy is being adopted by an increasing number of farmers leading to minimal herbicide dependence (Kumar et al., 2021). Weeds are highly responsive to management practices; thus, adoption of diverse approaches and harnessing the synergistic effect of each control tactic will help achieve long-term and sustainable weed management. The diverse tactics to manage weeds include use of clean and high-quality seeds that are free from weed seed contaminants and asexual propagules, proper tillage operations, stale seedbed technique, field sanitation, physical and mechanical weeding, mulching, soil solarization, intercropping, crop rotation, alternate wetting and drying of field, and use of biological control agents such as mycoherbicides, insects, and other weeds through allelopathy. Aside from these tactics, other innovative strategies to attain a more sustainable weed management in SEA are discussed below.

Use of weed competitive and allelopathic rice cultivars and increasing weed competitiveness by seed priming is an additional strategy for a sustainable weed management in rice. In direct-seeded and aerobic rice ecosystems, where weeds are the major pest due to the limited water supply to suppress weed growth, the use of weed competitive cultivars that can out-compete weeds provide alternative solutions to the unavailability of herbicides and achieve higher grain yields (Dimaano et al., 2017; 2020a). Success in the development of weed-competitive rice cultivars for SEA countries will offer an effective new strategy to manage weeds by single herbicide application thus reducing herbicide use and production costs and preventing the development of herbicide resistance.

Site-specific weed management (SSWM) systems take into consideration the spatial variability and temporal dynamics of weed populations thus allow weed mapping and site-specific herbicide spraying resulting in lower herbicide usage and costs. SSWM harnesses sensor technologies such as 3D cameras, artificial intelligence (AI) for weed classification, and computer-based decision algorithms to allow more precise spraying and hoeing operations (Gerhards et al., 2022). Use of computer-based programs and mobile applications to aid farmers and agriculture-practitioners on weed identification based on image recognition, weed canopy cover estimation, sprayer calibration, and herbicide computation are handy tools for correctly identifying weed species, deciding on critical threshold levels and proper timing of weed control, and executing more accurate and efficient herbicide applications, respectively.

SEA is still far behind in terms of using robotics in weed management. However, this promising human-labor saving technology can be a future effective strategy that can be pursued to combat weeds. In developed countries, use of robots and smart-technologies are already being adopted by organic vegetable farmers. Some prototypes available for use include Robocrop InRow Weeder, Dino, Hortibot, and BoniRob (Kushwaha, 2019; Muscalu et al., 2019). In neighboring developed Asian countries such as China, Japan, and South Korea, several prototypes of robotic weeders are also being developed. Utilization of such technology in SEA will be a promising alternative to the high usage of herbicides and soaring labor costs. Simpler and smaller robotic weeder prototypes may be developed for small-scale farming which constitutes most of SEA agricultural settings.

5.1 Sustainable herbicide management

The use of herbicides is considered as the most effective, economic and practical means to control weeds (Heap, 2014); however, sustainability of herbicide use is being threatened by the development of herbicide resistance in weed populations. Herbicide resistance particularly due to target-site substitutions can be resolved and mitigated by alternating different herbicides belonging to different MOAs through herbicide rotations, mix or sequential applications. However, sequential applications of herbicides occasionally also lead to multiple resistance problems wherein a single population accumulates target-site mutations that confer resistance to several herbicides belonging to different MOAs. Such target-site based multiple herbicide resistance cases were reported in some agronomically-important weeds such as in *Amaranthus tuberculatus* (Moq.) JD Sauer due to an acetolactate synthase (ALS) substitution and a protoporphyrinogen oxidase deletion (Shergill et al., 2018), and in *Alopecurus japonicus* Steud. and *E. crus-galli* due to ALS and acetyl-CoA carboxylase (ACCase) substitutions (Feng et al., 2016; Fang et al., 2019; 2020). This is an emerging challenge that needs to be addressed by providing more herbicide options and more intelligent herbicide combinations and sequential applications. Mixing more than two compatible MOAs in herbicide formulations or as tank-mixtures would significantly lower the probability for a weed population to develop resistance to specific herbicides. Combining herbicide control strategies with other non-herbicide control options would also help mitigate and slow down the evolution of resistance in weed populations.

An even bigger threat to the sustainability of herbicide use is the herbicide resistance due to metabolism-based mechanisms that endow resistance to existing, new and soon-to-be-discovered herbicides and further restricts the already limited herbicide options of farmers for selective weed control. In other words, metabolic herbicide resistance compromises the well-known strategy in controlling and mitigating herbicide resistance by rotating herbicide MOAs or applying herbicides in different mixtures or sequences. In this case, a weed population that has enhanced activity of herbicide metabolizing enzymes cannot be effectively controlled even if applied by mixed or alternate or sequential applications of various MOAs. To solve this problem, an effective strategy is to counteract the activity of the herbicide-metabolizing enzymes by the application of chemical synergists that inhibit them (Yu, Powles, 2014). For example, herbicide resistance due to the activity of cytochrome 450s can be reversed by the activity of P450 inhibitors such as malathion, piperonyl butoxide, aminobenzotriazole, and phorate (Christopher et al., 1994; Preston et al., 1996; Busi et al., 2017), whereas resistance due to the activity of glutathione S-transferases can be reversed by 4-chloro-7-nitrobenzoxadiazole (Cummins et al., 2013). Hence, identification and use of more effective chemical synergists to complement the existing herbicide active ingredients can be one the strategies to carry out to combat metabolism-based herbicide resistance and consequently attain a more sustainable herbicide use.

Presently, it is practically impossible to predict the development of herbicide resistance in weed species. However, thorough understanding of the molecular basis of herbicide resistance will allow prediction of the development of resistance in weeds (Dimaano et al., 2020b). Through molecular and biotechnological methods, detailed information on the specific plant enzymes involved in detoxification of wide herbicide substrates may be attained and will be useful in predicting herbicide resistance cases. Prediction of herbicide resistance was successfully demonstrated in *Echinochloa phyllopogon* (Stapf.) Koso-Pol. by functional characterization of the cytochrome P450 enzymes (Dimaano et al., 2020b) and may be performed in other agronomically-important weed species by characterization of other herbicide metabolizing enzymes such as glutathione S-transferases, glycosyl transferases, etc. Furthermore, knowing the specific herbicide substrates of these metabolizing enzymes in weeds will allow proper identification of the appropriate herbicides that can be effective to control the resistant weed populations.

5.2 Herbicide product stewardship and information campaigns on sustainable herbicide use

Responsible herbicide-use by end-users partnered with product stewardship by the private companies is a key factor to sustainable herbicide management. The major goal in stewardship is to maximize the benefits from herbicide products and minimize any risk such as environmental degradation, public health concerns and herbicide resistance development. Private companies in partnership with research institutions, academe and government sectors in SEA are joining hands to educate farmers and end-users through information campaigns through print materials and infographics on effective and responsible herbicide use. Further, farmers field schools, seminars and training incorporate topics on proper application of herbicides according to pesticide labels and recommendations. Farmers learn through first-hand experience and through actual demonstrations; thus, actual field set-ups and practical lessons greatly improve their skills in herbicide and sustainable herbicide management.

The use of GM herbicide tolerant (HT) crops is being widely adopted in the Philippines, Vietnam, Indonesia, and Myanmar (ISAAA, 2022). The most widely adopted HT crop is the Round-up Ready corn that allows the single herbicide glyphosate to provide broad-spectrum control of weeds. However, over-reliance on a single MOA herbicide leads to herbicide resistance problems and threatens the success of planting HT crops. Sustainability of planting herbicide-tolerant crops may be achieved by stacking traits for tolerance to two or more herbicide MOA. Complementary herbicide active ingredients that are safe to HT crops and can provide excellent weed control must also be available as alternative options. Furthermore, field monitoring and resistance surveys should also be regularly conducted to offset the development of herbicide resistance and ensure the sustainability of HT crop technology.

5.3 Regulation of Herbicide Registration

Herbicide product failures not related to herbicide resistance may be due to inaccurate application of farmers in terms of wrong amount of active ingredient, incorrect calibrations of sprayers, and erroneous application timings. In SEA, not all countries have a systematic and strict regulation on herbicide importation, registration and approval (Food and Agriculture Organization, 2013). As a consequence, unregistered imported herbicide products are being widely sold to local farmers (Annamalai et al., 2021). This may lead to problems such as improper herbicide use leading to crop injury, non-effectivity to target weeds, and herbicide resistance problems particularly for products not properly tested on actual field conditions. In the Philippines, strict regulation is being implemented on the proper registration and release of a new active ingredient in the market which imposes field trials on crop safety and bioefficacy, safety to non-target site organisms, and safety to the environment (Fertilizer and Pesticide Authority, 2022). Herbicide labeling, as an integral part of herbicide product registration, currently requires indicating the specific herbicide MOA to better guide farmers in decision-making and planning which herbicides to use considering resistance management.

6. Framework for sustainable weed management in SEA

Managing weed problems successfully has always been the goal. This means reducing the negative impact of weeds on crop yield thereby increasing productivity and profitability. Development of a sustainable weed management program has been the desire of many weed scientists around the world. As weed scientists, we propose a framework for a sustainable weed management in the region (Figure 2). This framework recognizes the uniqueness of weed and cropping situations in the region; the contribution of the various stakeholders such as farmers, government agencies, the academe, private industry and non-government organizations (NGOs) towards the attainment of one goal; and the importance of partnerships and collaboration in conducting and funding research initiatives and policy formulation. We envision a system wherein there is continuous farmer education on the judicious use of herbicides as well as awareness on the many options available in managing weed problems. There should be concerted research and development efforts geared towards creating technologies that are available to farmers. Active stewardship, particularly on herbicide programs is essential and should be encouraged if not enforced. And lastly there should be appropriate and adequate regulation to guard against misuse of herbicides and at the same time permit registration of new herbicide formulations in a timely manner.

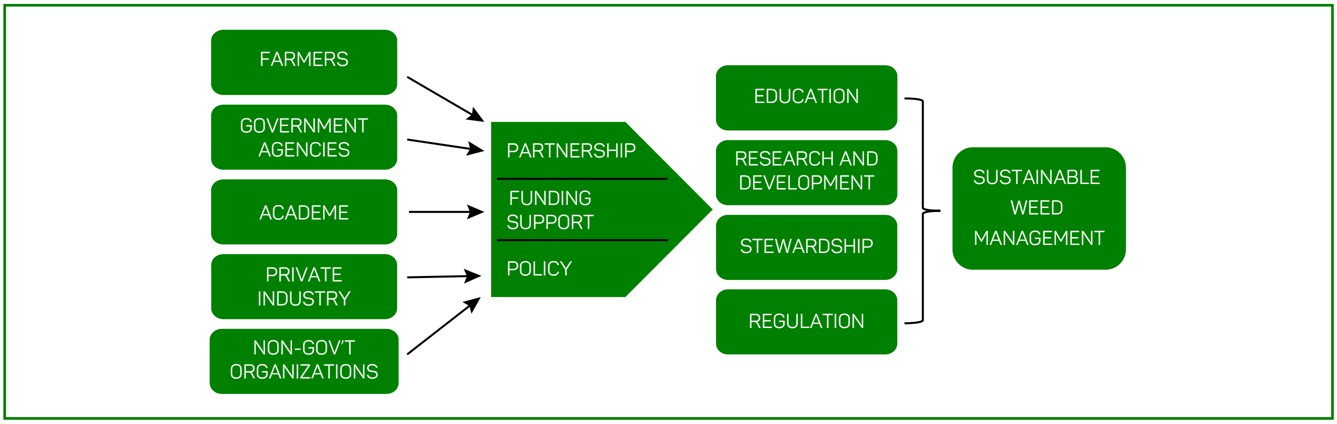


Figure 2 - Sustainable weed management framework for Southeast Asia

7. Conclusion

SEA has favorable climatic conditions and resource endowments that allow it to produce diverse crops including the two major staples, rice and corn. Weeds cause yield losses contributing to large economic losses in agriculture. Prior to the introduction of herbicides, farmers relied on hand weeding and manual methods to control weeds. The introduction of herbicides in the late 1940s revolutionized weed management. The 1980s saw the entry of diverse herbicide groups ranging from broad spectrum to highly selective ones, which provided a cost-effective and convenient method for weed management.

In recent years, the use of herbicides to manage weeds in the rice-based, corn-based and perennial crops-based systems has been increasing. The herbicides commonly used in these cropping systems have not changed much but there has been a shift towards highly selective herbicides in rice-based and corn-based systems. Glyphosate, commonly used in perennial crop-based systems, is now used in rice and corn, prior to crop establishment and in GM corn. The continuous use of these resulted in herbicide resistance in weeds associated with rice, corn and perennial crops. To date, there are 37 unique cases of reported herbicide resistance involving 17 weed species and 30 active ingredients. Contamination of surface and ground water and bioaccumulation in rice field frogs and crabs were also documented.

Limited investments to educate farmers on proper use of herbicides and integrated weed management and lax implementation of pesticide policies and regulations have both contributed to unsustainable weed management which leads to economic losses, shifts in weed flora, development of herbicide resistance, and adverse effects to the environment. Integrated weed management approach, combining direct and indirect control methods, and based on the critical period of crop-weed competition, helps overcome weed problems, reduces costs to farmers and minimizes harm to the environment. The application of spatial technologies and AI offers a huge potential for site-specific and precise weed management in the future.

Herbicides will remain to be a key strategy for weed management in the three major cropping systems in the region. Hence, it is imperative to move towards sustainable herbicide management through responsible herbicide-use by end-users and product stewardship by the private companies to maximize the benefits from herbicide products and minimize any risk such as environmental degradation, public health concerns, and herbicide resistance development. The partnership is taking root in some countries in the region but more needs to be done. A sustainable weed management framework is needed to involve the various stakeholders in forging strong partnership, formulating and implementing the fair policies and regulations for the industry, investing in research and development to generate a pipeline of innovative and affordable technologies and educating farmers and other industry players about the value of herbicide as a resource and their responsibility as stewards of sustainable weed management.

Author's contribution

All authors are involved in the conceptualization, writing and editing of this review paper.

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