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Survey of herbicide-resistant weed management in oil palm estates from Peninsular Malaysia and Indonesia

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Abstract: Background: The use of herbicides is a common practice to control weeds in oil palm plantation. However, high dependency on herbicides causes intense selection pressure, which could lead to the evolution of herbicide resistance in weed. **Objective:** To assess planters' understanding of herbicide resistance management practices. **Methods:** Data were gathered via the application of questionnaires during the 2022 growing season to planters working with oil palm in Peninsular Malaysia and Indonesia. There were 101 respondents, covering about 14 states. **Results:** Planters (75 to 85% respondents) found herbicide rotation, cover crops, and pre-emergence herbicide application effective against herbicide-resistant weeds, but high herbicide costs hindered their selection of chemical solutions. Peninsular Malaysia planters (30 to 78% respondents) reported five major putative resistant weeds such as *Eleusine indica* (L.) Gaertn., *Clidemia hirta* (L.) D. Don., *Melastoma malabathricum* (L.), *Ischaemum muticum* (L.), and *Asystasia gangetica* (L.) T. Anderson. Indonesian planters (28 to 43% respondents) faced putative resistance in *E. indica* and *C. hirta*. Peninsular Malaysia's higher incidence of putative resistance was linked to insufficient knowledge of herbicide classification, less use of tank-mixed herbicides, and reduced herbicide rates, potentially fostering resistance evolution. **Conclusions:** The survey revealed that Indonesia planters possess a better understanding of herbicide resistance management as compared to Peninsular Malaysia planters. There is a need to increase awareness on sustainable use of herbicides through training and educational programs for planters in Peninsular Malaysia.

Keywords: *Clidemia Hirta*; *Eleusine Indica*; Herbicide Classification; Herbicide Rotation; Herbicide Resistance; Tank Mixture

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1. Introduction

Elaeis guineensis (Jacq.), commonly referred to as oil palm, stands as the predominant oil crop globally, constituting approximately 40% of the total traded vegetable oil (Murphy et al., 2021). Palm oils are integral to the diets of many individuals and find extensive application in non-food sectors, notably in the production of cleaning and sanitizing products. Given the escalating demand for palm oil in both food and industrial domains, oil palm cultivation spans various countries across Africa, South America, and Southeast Asia, with Indonesia and Malaysia largely dominating the global market (Ritchie, 2021). In 2018, global oil palm production hit 72 million tonnes, with Indonesia contributing 57% (41 million tonnes) and Malaysia contributing 27% (20 million tonnes) (Ritchie, 2021). As of 2022, Indonesia boasted approximately 15 million hectares of oil palm plantations, yielding an annual production of 46 million tonnes of palm oil (Badan Pusat Statistik Indonesia, 2023). Ownership distribution in Indonesian oil palm plantations reveals that private companies hold 55.9%, smallholders account for 40.5%, and the government owns 3.6% (Badan Pusat Statistik Indonesia, 2023). Malaysia, the world's second-largest palm oil producer after Indonesia, maintains palm oil plantations spanning over 5.67 million hectares as of 2022 (Kadir, 2022). Sarawak leads in oil palm plantation area within Malaysia, covering 1.62 million hectares or 28.6% of the total, followed by Sabah with 1.51 million hectares or 26.6%, while Peninsular Malaysia accounts for 2.54 million hectares or 44.8% (Kadir, 2022). Crude palm oil production reached 18.45 million tonnes, with an average fresh fruit bunches yield of 15.49 tonnes per hectare, and total palm oil exports, including other palm-based products, amounted to 24.72 million tonnes (Kadir, 2022). In 2021, Malaysia's total oil palm plantation area was 5.7 million hectares, with private and government/state agency estates covering 73.2%, individual smallholders holding 15.1%, and organized smallholders managing 11.7% (Parveez et al., 2022). Despite Indonesia and Malaysia's substantial oil palm output, the presence of weeds in oil palm plantations poses a potential threat to productivity. Weeds, characterized by vigorous growth, hinder sunlight penetration, and compete with desirable plants for nutrients (Ruzlan, Hamdani, 2020).

Weeds in oil palm plantations detrimentally impact both the quantity and quality of fresh fruit bunches, impede plant development, increase vulnerability to pests and diseases, disrupt water usage, and elevate agricultural costs (Hakim et al., 2020). Assessing the impact of weeds on oil palms proves challenging due to its extended economic lifespan, typically spanning 20 to 30 years (Kuan et al., 1991). Nevertheless, Sahid et al. (1992) documented production reductions of 6 to 20% in oil palm farms due to intense weed competition. Furthermore, effective management of weed species like *Asystasia gangetica* (L.) T. Anderson had the potential to enhance fresh fruit bunch production by 12% (Kustyanti, Horne, 1992). Effective weed management hinges on plant identification, understanding the plant life cycle, and selecting appropriate control strategies. Despite the utilization of biological, mechanical, and cultural methods, herbicide spraying remains the primary weed management approach in oil palm plantations. Herbicides such as glyphosate, glufosinate, metsulfuron-methyl, and the recently banned paraquat are extensively used in oil palm plantations (Ruzlan, Hamdani, 2020).

However, excessive reliance on herbicides could lead to the emergence of herbicide-resistant weeds. This phenomenon is intensified due to the monoculture of oil palm in Malaysia and Indonesia. To date, eight weed biotypes have evolved herbicide resistance in the oil palm plantations or nurseries in Malaysia, including four weed species of *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 and Sahid, 2010) and *Clidemia hirta* (L.) D. Don (Ramadzan et al., 2012) in the states of Pahang, Kedah, Selangor, Perak, Johor, and Sarawak, Terengganu, Kelantan in Malaysia (Chuah and Sahid, 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). Similarly, *E. indica* populations resistant to glyphosate in oil palm plantation in North Sumatra, Indonesia have been documented (Tampubolon et al., 2019; Purba, Sipayung, 2022).

The emergence of herbicide-resistant weeds in oil palm plantations can have substantial economic and environmental impacts. Economically, it can lead to reduced crop yields and higher weed management costs due to diminished herbicide efficacy. Environmentally, increased herbicide use resulting from resistance may lead to a loss of plant biodiversity and the degradation of soil health. Consequently, it is crucial to minimize the risks of herbicide resistance through effective weed management strategies. However, there is still limited information available on the planters' understanding regarding herbicide resistance management, the challenges faced by them, and the current status of herbicide-resistant weeds in oil palm plantations. Recognizing and addressing these issues are essential for implementing an improved weed management strategy aimed at slowing down the evolution of herbicide-resistant weeds while ensuring the sustainable use of herbicides. This survey was carried out to evaluate planters' knowledge and management practices regarding herbicide-resistant weeds in oil palm estates in Peninsular Malaysia and Indonesia. The survey is anticipated to yield valuable insights for researchers, extension officers, plantation managers, and policy makers. It will help identify knowledge gaps among planters and deficiencies within support systems that impede sustainable management of resistant weeds in oil palm plantations.

2. Materials and Methods

2.1 Study Sites

The survey encompassed significant oil palm planted states such as Kedah, Terengganu, Perak, Pahang, Negeri Sembilan, and Johor in Peninsular Malaysia, as well as Aceh, Sumatera, Riau, Jambi, Belitung, Bengkulu, Kalimantan, and Papua in Indonesia (Figure 1). These surveyed states collectively accounted for 87% (2.22 million ha) and 65% (9.5 million ha) of oil palm planted areas in Peninsular Malaysia and Indonesia, respectively.

2.2 Survey Design

A survey was conducted using a structured survey questionnaire and sent randomly to oil palm estate growers through google forms in 2022. Prior to data collection, a pilot test was conducted to assess the suitability of the questions, their clarity, and the probability of obtaining high-quality data. Thirty-five planters were selected for the pilot test, a sample size consistent with the recommended range by Kieser and Wassmer (1996). The questionnaire was subsequently sent to participants from government and private estates. A total of 27 respondents were obtained from oil palm estates in Peninsular Malaysia, while a total of 74 respondents were from oil palm estates in Indonesia.

The survey had 10 questions organised into two sections: (1) respondent's demographic, and (2) the occurrence and management of herbicide-resistant weed. Part 1 of the study required the growers to provide their sociodemographic details including age, level of education, experience in oil palm cultivation, main occupation, and oil palm cultivation area. In part 2, planters were surveyed about their awareness on the emergence of herbicide resistance weed, the classification of herbicides based on their mode of action, and their compliance with the appropriate herbicide application rate. Next, the planters were surveyed regarding their implementation of agronomic techniques to combat herbicide resistance in weeds, challenges faced by respondents in selecting appropriate herbicides to effectively control resistant weed species, as well as the occurrence of problematic weeds despite multiple herbicide applications.

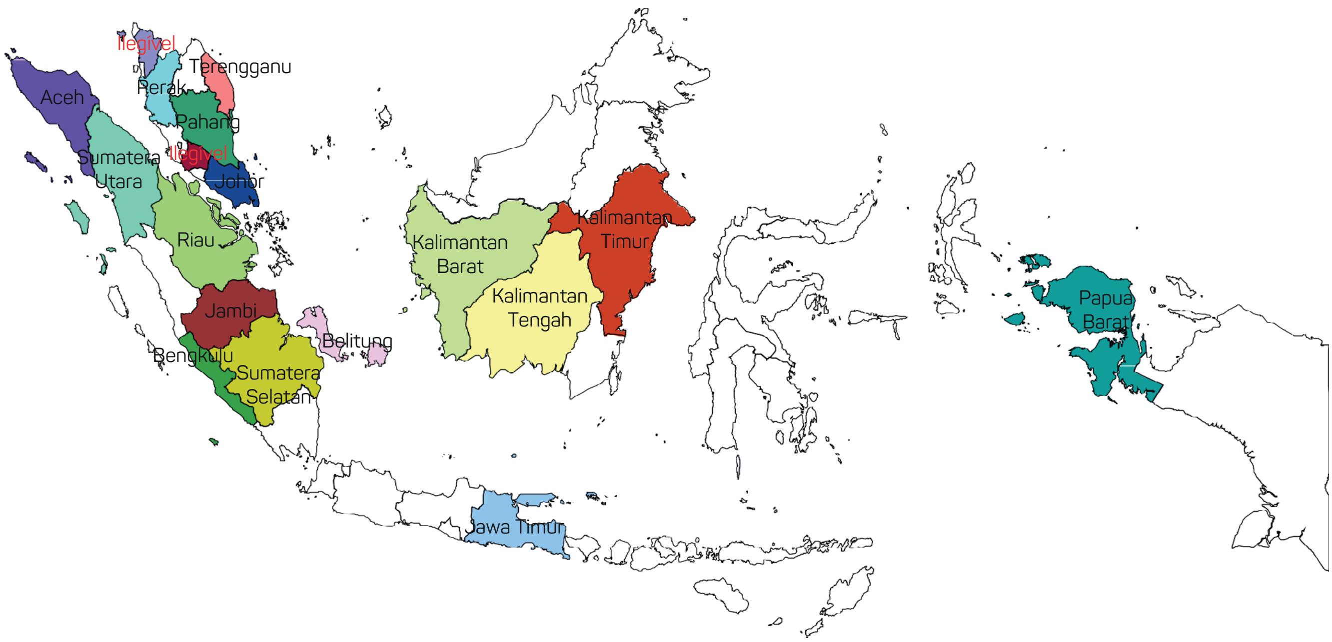

Figure 1 - Oil palm planted areas surveyed in Peninsular Malaysia and Indonesia

3. Experimental design and Statistical analysis

The data collected from the questionnaire underwent coding and analysis using Statistical Package for Social Sciences (SPSS) version 25. Sociodemographic characteristics were examined through a chi-square test to explore the relationship between variables across the study countries. A chi-square analysis was also employed to assess the disparities in planters' awareness regarding the occurrence of herbicide resistance, the classification of herbicides based on mode of action, and their adherence to applying the recommended herbicide rate between two countries. The Kruskal-Wallis test with pairwise comparison was utilized to evaluate discrepancies in deterrents encountered by respondents when selecting appropriate herbicides to manage resistant weed species.

4. Results and Discussion

4.1 Sociodemographic Characteristics of Planters

The sociodemographic characteristics of surveyed planters from estates are presented in Table 1. The survey findings indicate 89% of respondents were primarily engaged in oil palm-related occupations in Peninsular Malaysia. By contrast, all respondents from Indonesia worked within the oil palm sector. Additionally, estate planters from both regions had varying levels of farming experience ($P<0.01$). In Peninsular Malaysia, the majority (90%) of planters had between less than 5 years to 20 years of experience, whereas in Indonesia, 80% of planters had less than 5 years to 15 years of experience. However, estates in both countries were primarily managed by planters aged between 21 to 50 years old, constituting 92% of respondents. On the other hand, the extent of oil palm cultivation area differs significantly ($P<0.001$) between the two countries. The majority (97%) of planters from Peninsular Malaysia cultivated oil palm on land ranging from 500 to 5,000 hectares, whereas 97% of planters from Indonesia managed cultivation areas ranging from 100 to over 5,000 hectares. Furthermore, there are disparities in the education levels of planters between the two countries ($P<0.001$). In Indonesia, the majority of planters had education levels ranging from diploma (82%) to higher education (11%), while in Peninsular Malaysia, planters' education levels ranged from secondary education (22%) to diploma (41%) and higher education (37%).

4.2 Awareness on Herbicide-Resistant Weed and Herbicide Application Practice

Table 2 presents the planters' awareness regarding the occurrence of herbicide resistance, the classification of herbicides based on mode of action, and their adherence to applying the recommended herbicide rate. The majority of planters from both countries demonstrated a high level of awareness in recognizing the occurrence of herbicide-resistant weeds in their estates. Specifically, 100% of planters in Peninsular Malaysia and 97% of planters in Indonesia were aware of the occurrences of herbicide-resistant weeds. In Indonesia, planters exhibited a notably high awareness of the classification of herbicides based on mode of action (MOA), with 97% of respondents indicating familiarity with this aspect. However, awareness regarding the classification of herbicides based on MOA among planters in Peninsular Malaysia was slightly lower ($P<0.05$), accounting for 78% of respondents.

Table 1 - Sociodemographic characteristics of surveyed planters from estates						
Profile	Peninsular Malaysia (n=27)		Indonesia (n=74)		Chi square	
	Freq.	%	Freq.	%	χ^2	P value
Age (yr.)						
21–30	6	22	34	46	7.46	0.11400
31–40	16	59	23	31	-	-
41–50	3	11	11	15	-	-
51–60	2	7	5	7	-	-
>60	0	0	1	1	-	-
Education background						
Primary	0	0	1	1	22.05	0.00006
Secondary	6	22	2	3	-	-
Diploma	11	41	61	82	-	-
Degree and above	10	37	8	11	-	-
Farming experience (yr.)						
<5	4	15	29	39	16.59	0.01100
6–10	7	26	20	27	-	-
11–15	5	19	10	14	-	-
16–20	8	30	4	5	-	-
21–25	1	4	5	7	-	-
26–30	0	0	4	5	-	-
>30	2	7	2	3	-	-
Primary job						
Oil palm related	24	89	74	100	8.47	0.00400
Oil palm not related	3	11	0	0	-	-
Area of oil palm cultivation (ha)						
<100	0	0	2	3	20.37	0.0004
100–500	1	4	10	14	-	-
500–1,000	5	19	30	41	-	-
100–5,000	21	78	21	28	-	-
>5,000	0	0	10	14	-	-

The majority of planters in both Peninsular Malaysia (78%) and Indonesia (84%) reported adhering to herbicide application at the recommended rate. However, a small percentage of planters ($P<0.05$) in Peninsular Malaysia (7%) chose to reduce the recommended herbicide rate, while no planters in Indonesia adopted this method. Conversely, some planters increased the recommended herbicide rate. Applying herbicides at higher-than-recommended dosages can significantly increase the mortality rate of targeted weeds. However, as highlighted by Purba and Sipayung (2022), in cases where weeds have developed resistance to herbicides, the efficacy of weed control, even at increased application rates, may be low. Furthermore, this approach can lead to higher input expenses and labor costs. By contrast, applying herbicides at doses lower than the recommended rate (sublethal doses) can result in a significant number of weeds surviving, potentially leading to the evolution of herbicide resistance. Studies on the evolution of herbicide-resistant weeds through repeated application of low herbicide dosages in oil palm plantations are still scarce. Nevertheless, several studies have documented cases of field-evolved herbicide-resistant weeds following continuous application of herbicides at lower-than-recommended rates (Manalil et al., 2011; Ashworth et al., 2016).

4.3 Agronomic Practices of Herbicide-Resistant Weed Management

Table 3 outlines the agronomic practices adopted by planters in Peninsular Malaysia and Indonesia to manage herbicide-resistant weeds in their estates. The findings

Table 2 - Awareness of planters on occurrence of herbicide resistance, classification of herbicide based on mode of action and their adherence to apply recommended rate of herbicide

Category	Peninsular Malaysia (n=27)	Indonesia (n=74)	Chi square	
	%		χ^2	P value
Awareness on occurrence of herbicide resistance	100	97	0.74	0.388
Awareness on classification of herbicide based on mode of action	78	97	10.33	0.001
Apply the recommended rate of herbicide	78	84	0.18	0.668
Reduce the recommended rate of herbicide	7	0	5.59	0.018
Increase the recommended rate herbicide	15	11	0.30	0.582

Table 3 - Agronomic practice of planters to manage herbicide resistance in weeds

Category	Peninsular Malaysia (n=27)	Indonesia (n=74)	Chi square	
	%		χ^2	P value
Rotate herbicides	81	85	11.73	0.039
Tank mixed herbicides/cocktail	67	89	-	-
Mulching	74	54	-	-
Livestock grazing	70	27	-	-
Cover crop	74	82	-	-
Good land preparation by spraying pre-emergence herbicides	70	73	-	-

reveal that the majority of planters (70–85%) from both countries recognize certain preferred agronomic strategies for addressing herbicide resistance in weeds, including rotating herbicides, utilizing cover crops, and implementing thorough field preparation with pre-emergence herbicides. However, in Peninsular Malaysia, a significant number of planters reported using mulching (74%) and animal grazing (70%) as methods for managing herbicide-resistant weeds. Conversely, the majority of planters (89%) in Indonesia opted for the practice of mixing herbicides in a tank as another method to control herbicide-resistant weed.

Widely acknowledged strategies for managing herbicide resistance include the implementation of tank mixtures and herbicide rotation. Previous studies have provided evidence that mixtures offer a more effective approach to delaying resistance evolution compared to single-use or simple herbicide rotations (Busi et al., 2020). Mixing herbicides has been observed to be more successful in controlling *E. indica* compared to using a single herbicide at oil palm plantations in North Sumatra, Indonesia (Tampubolon et al., 2020). Hence, the prevalence of tank mixed herbicides among planters in Indonesia might be attributed to this factor compared to planters in Peninsular Malaysia.

It is not recommended to mix two herbicides without first determining if they are compatible since they may work antagonistically, additively, or synergistically (Dilipkumar et al., 2020). The practice of tank mixing requires use of multiple herbicides, which increases the complexity of the weed management system, thus requiring a certain degree of expertise and knowledge to match herbicides and effective modes of action with target species (Norsworthy et al., 2012). Additionally, a prior study on a weed management program at an oil palm plantation in Peninsular Malaysia found that the combination of chemical, cultural (e.g., mulching), and biological control (e.g., animal grazing, such as sheep and cattle) produced lower costs of weed control strategies compared to the use of chemicals alone (Ruzlan, Hamdani, 2020). Another study has shown that oil palm-cattle integration may save total weeding costs by 5 to 69% when compared to chemical control (Devendra, 2011). The affordable cost of weed control achieved through cultural and biological methods might be the reason planters in Peninsular Malaysia opted for the practice of mulching and livestock grazing at the plantation compared to planters in Indonesia.

4.4 Constraints of Herbicide-Resistant Weed Management

Table 4 shows the constraints encountered by planters when selecting herbicides for managing herbicide-resistant weeds. The severity of constraints was categorized into four grades (1 to 4), with 1 indicating no difficulty and 4 representing very high difficulty. The majority of respondents highlighted that expensive herbicide products posed a significant challenge for planters in both Peninsular Malaysia and Indonesia, with average ratings ranging from 3.04 to 3.23, respectively.

Table 4 - Difficulties or deterrents experienced by respondents in choosing the right herbicides to control the resistant weed species

Type of difficulty	Abundance category			
	Peninsular Malaysia (n=27)		Indonesia (n=74)	
	Avg	SD	Avg	SD
Lack of knowledge about the herbicides	2.52a	0.753	2.45a	0.862
Difficult to understand information on herbicide's label	2.26a	0.764	2.08a	0.736
Herbicides products that are expensive	3.04b	0.854	3.23b	0.853
Misleading information from sales representatives of agrochemical companies	2.52a	0.643	2.23a	0.713
Guidelines provided by the government agencies involved are too general	2.56a	0.577	2.35a	1.026

Categories: 1 = none; 2 = low; 3 = high; 4 = very high. Means within a column followed by the same letter are not different at P = 0.05 using the Kruskal--Wallis test with pairwise comparison

The repeated application of a single herbicide with the same mode of action (MOA) over an extended period is often linked to the development of herbicide resistance (Beckie, 2006). Utilizing herbicides with different MOAs, preferably in combination as mixes, and alternatively in rotation as part of a weed control program, might delay the development of resistance in certain scenarios (Norsworthy et al., 2012). A previous study by Kniss et al. (2022) indicated that using an effective MOA mixture in field crops would increase the cost of herbicides by at least two-fold, even in the absence of any pre-existing herbicide resistance, and the expense would escalate considerably more if there were already resistance to herbicides in a field. In this context, government agencies and private sectors should collaborate to provide incentives for planters to enhance their purchasing power toward a wider range of affordable and effective herbicides to manage resistant weed species, thereby achieving the long-term goal of efficient weed control.

4.5 Problematic Weed Species

The current study unveils the persistence of numerous weed species resilient to herbicides, persisting even after multiple rounds of spraying, as delineated in Table 5. Two problematic weed species were identified by the majority of planters in Indonesia, namely *E. indica* and *C. hirta*, accounting for 43% and 28% of respondents, respectively. Conversely, in Peninsular Malaysia, the majority of planters reported more than two problematic weed species, including *E. indica* (78% respondents), *C. hirta* (70% respondents), *Melastoma malabathricum* (L.) (52% respondents), *Ischaemum muticum* (L.) (41% respondents), and *A. gangetica* (30% respondents).

Previous research has documented cases of *E. indica* populations resistant to glyphosate in oil palm plantations in North Sumatra, Indonesia (Tampubolon et al., 2019; Purba, Sipayung, 2022). Several weed species, including *C. hirta* and *E. indica*, have demonstrated resistance to multiple herbicide applications in oil palm plantations located in Peninsular Malaysia (Chuah and Sahid, 2010; Ramadzan et al., 2012). Similarly, the present study reveals that three weed species from Peninsular Malaysia—*M. malabathricum*, *I. muticum*, and

Table 5 - Problematic and survived weed species reported by respondent despite having sprayed herbicides for several rounds

Weed species	Peninsular Malaysia (n=27)	Indonesia (n=74)
	%	
Eleusine indica (L.) Gaertn.	78	43
Clidemia hirta (L.) D. Don	70	28
Melastoma malabathricum L.	52	19
Ischaemum muticum L.	41	12
Asystasia gangetica (L.) T. Anderson	30	11
Echinochloa colona (L.) Link	19	9
Borreria latifolia (Aubl.) K. Schum.	15	11
Cleome rutidosperma DC.	15	4
Chromolaena odorata (L.) R.M.King & H.Rob.	11	12
Oldenlandia verticillata L.	11	7
Ageratum albidum (DC.) Hemsl.	7	12
Ottochloa nodosa (Kunth) Dandy	0	11
Stenochlaena palustris (Burm. f.) Bedd.	0	8
Cyperus acholiensis Larridon	0	3
Philodendron scandens K. Koch & Sello	0	1
Dianella acutifolia Schlittler	0	1
Caladium andreanum Bogner	0	1
Derris elliptica (Wall.) Benth.	0	1
Syngonium podophyllum Schott	0	1
Centotheca lappacea (L.) Desv.	0	1
Bambusa affinis Munro	0	1

A. gangetica—and one weed species, *C. hirta*, from Indonesia may have developed resistance to herbicides. Further study is needed to confirm the occurrence of herbicide resistance in these weeds through dose response bioassay.

The emergence of developed putative herbicide-resistant weed species may coincide with the challenge of selecting the right herbicide due to expensive herbicide products, leading planters to persistently use the same herbicide over time without transitioning to alternative options. The increased occurrence of evolved putative herbicide-resistant weeds in plantations across Peninsular Malaysia, in contrast to Indonesia, could be linked to the consistent exposure of targeted weeds to sublethal levels of herbicides by some planters. Furthermore, the elevated presence of these problematic weeds in Peninsular Malaysia might align with specific agronomic methods practiced in these plantations. Planters in Peninsular Malaysia lack a comprehensive understanding of herbicide classification based on mode of action and tend to utilize tank mixed herbicides less frequently, despite evidence demonstrating their superior effectiveness compared to herbicide rotation. This current finding suggests that various measures, including selecting the right herbicides and adopting best agronomic practices, must be undertaken by government agencies and planters to slow down further evolution of any new herbicide-resistant weed species.

5. Conclusions

This survey offered deeper insights into the management of herbicide-resistant weeds among oil palm planters in Peninsular Malaysia and Indonesia. It shed light on planters' comprehension of herbicide resistance, the challenges impeding the adoption of sustainable weed management practices, and the factors driving the evolution of herbicide resistance. The majority of planters, across both regions, demonstrated awareness of herbicide resistance, indicating a widespread recognition of this issue. However, the sustainable utilization of chemical weed control methods faces hurdles due to the high costs of herbicides, limiting the range of available options. This circumstance has directly contributed to the evolution of major putative herbicide-resistant weeds such as *E. indica*, *C. hirta*, *M. malabathricum*, *I. muticum*, and *A. gangetica*. The higher incidence of these problematic weeds in Peninsular Malaysia was due to a lack of knowledge about herbicide classification based on mode of action, less use of herbicide mixture and the application of herbicides at reduced rates. Therefore, comprehensive educational programs on sustainable use of herbicide are needed for planters in Peninsular Malaysia.

Author's contributions

All authors read and agreed to the published version of the manuscript. CTS, and EP: conceptualization of the manuscript and development of the methodology. NY, NKCMR, SNA, MSAMS, JTP, NS: data collection. CTS: data analysis, data interpretation. CTS, and EP: funding acquisition and resources. SAP: project administration. CTS, and EP: supervision. CTS, EP, and SAP: writing the original draft of the manuscript. CTS, EP, and SAP: writing, review, and editing.

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