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Review Article

Herbicide Resistance in Malaysian Oil Palm Plantations: A Comprehensive Review of Current Challenges and Management Strategies

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ABSTRACT

Elaeis guineensis Jacq. (oil palm) is the principal export crop in Malaysia, accounting for a significant percentage of GDP. However, its production is hampered by various factors, in particular weeds. Weed control in Malaysian oil palm plantations predominantly relies on herbicides. The excessive herbicide use has driven the emergence of herbicide-resistant weed species in plantations. Repeated use of herbicides such as glyphosate, glufosinate-ammonium, metsulfuron-methyl, and paraquat has led to the prevalence of resistant weed biotypes. Herbicide resistance in weeds is a growing global concern, threatening food safety and security, agricultural sustainability, and the environment. While much of the focus has historically been on well-known resistant species, lesser-known weeds, particularly those infesting oil palms, also exhibit resistance, causing significant long-term impacts. However, research on these lesser-known species is limited, especially regarding their competitive effects, resistance status, and underlying resistance mechanisms. Focusing on these less-studied herbicide-resistant weed species is essential for effective crop management and the sustainability of oil palm cultivation. To address these challenges, this review explores the background of herbicide-resistant weeds in Malaysian oil palm plantations and examines integrated approaches for sustainable weed management. These strategies include cover cropping, targeted livestock grazing, and using herbicides in diverse modes of action. Integrating multiple management strategies, closely monitoring weed populations for early detection of resistance, and responding promptly

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to new detections are crucial steps in curbing the spread of herbicide-resistant weeds. Advances in molecular biology and precision agriculture practices will significantly enhance efforts in managing herbicide-resistant weeds.

Keywords: *Elaeis guineensis*, herbicide resistance, integrated weed management, Malaysia, management strategies, oil palm plantations, oil palm sustainability

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INTRODUCTION

Oil palm (Elaeis guineensis Jacq.) is a monocotyledonous perennial crop belonging to the Palm family, Arecaceae. Malaysia is the second largest palm oil producer, with a total planted area of 5.65 million hectares (Parveez et al., 2024). In 2023, the export volume was about 15 million tonnes, accounting for 29.5% of the global palm oil trade and contributing RM105 billion to the country's GDP (Parveez et al., 2024). These oils are used for cooking and various non-food purposes, such as animal feeds, cosmetics, detergents, and biodiesel (Murphy et al., 2021). Thus, the importance of this sector in driving the country's economic growth and development is undeniable.

However, palm oil production is threatened by herbicide resistance, which stems from excessive herbicide use in oil palm cultivation. It leads to reduced yields, increased management costs, biodiversity loss, and threats to food security and environmental sustainability (Dilipkumar et al., 2020; Seng et al., 2024; Tampubolon et al., 2024). Herbicide-resistant weeds are a significant challenge impacting management and productivity. They have been reported in major oil palm-producing countries like Indonesia, which shares similar agricultural practices with Malaysia (Casemiro et al., 2022). Indonesia has a lower overall incidence of resistance, with *Eleusine indica* (L.) Gaertn. (goosegrass) reported. However, resistance in *E. indica* is widespread, with numerous populations exhibiting resistance to both glyphosate and paraquat (Kurniadie et al., 2023; Umiyati et al., 2023). In contrast, Malaysia has documented resistance in four weed species, with three new cases emerging recently (Chuah et al., 2023; Heap, 2025; Seng et al., 2024). Therefore, this review evaluates the prevalence and impact of herbicide-resistant weeds in Malaysian oil palm plantations and explores integrated management strategies to mitigate this growing challenge.

Challenges in Oil Palm Cultivation

Given the increasing global demand for vegetable oils for food and industrial uses, it has become essential to maximise palm oil production. However, achieving this is a major challenge due to several constraints such as climate change, labour shortage, limited arable land, old age of crops, slow replanting process, and the occurrence of new and existing pests/diseases (Murphy et al., 2021; Parveez et al., 2024). Dilipkumar et al. (2020) identified weeds as a particular factor affecting productivity in oil palms.

Several studies have identified such weeds as *Ageratum conyzoides* L., *Asystasia gangetica* (L.) T. Anderson, *Chromolaena odorata* (L.) R.M. King and H. Rob., *Clidemia hirta* (L.) D. Don, *E. indica*, *Hedyotis verticillata* (L.) Lam, *Ischaemum timorense* L., *Melastoma malabathricum* L. and *Mikania micrantha* Kunth (Wibawa et al., 2010; Dilipkumar et al., 2020). If not controlled, these weeds compete with crops, reducing the quantity and quality of yields. They may also act as vectors of pests and pathogens that infest crops. Weeds also interfere with farming practices such as irrigation, fertiliser application, and harvesting (Rosli et al., 2010; Murphy et al., 2021).

Generally, weeds are controlled using various cultural, physical, biological, mechanical, and chemical strategies (Nobilly et al., 2022). However, physical and mechanical weed control methods are inefficient, labour-intensive, tedious, and weather-dependent, especially in commercial plantations, while biological and cultural methods are not particularly effective. Therefore, weed management in Malaysian oil palm heavily depends on herbicides because they are the most reliable and effective control method (Casemiro et al., 2022). Considering the significance of oil palm to Malaysia's economy, effective weed management is vital for the long-term productivity and sustainability of the oil palm plantations.

HERBICIDE RESISTANCE IN MALAYSIAN OIL PALM

Emergence of Herbicide Resistance

Malaysia is one of the top herbicide users in Southeast Asia due to its heavy dependence on herbicides involved in the cultivation of rice (*Oryza sativa* L.), rubber (*Hevea brasiliensis* (Willd. ex A. Juss.) Müll. Arg.), and oil palm (Casemiro et al., 2022). In 2021, herbicides constituted 70% of the total pesticide use in Malaysia (Food and Agriculture Organisation of the United Nations [FAO], 2023). The quick success of herbicides and ease of operation make them an attractive option in weed control. However, misuse of these chemicals has led to the emergence of herbicide-resistant weeds in oil palm plantations.

Herbicide resistance in weed populations occurs when the weeds are repeatedly exposed to the same herbicide or herbicides with similar modes of action, which imposes a selection pressure. Resistance in Malaysian oil palm plantations is linked to heavy reliance on herbicides, inadequate knowledge regarding herbicide classes, and improper application techniques (Seng et al., 2024). For example, resistance to metsulfuron-methyl in the *C. hirta* population in Jerantut, Pahang, was observed after continuous use for at least five consecutive years (Ramadzan et al., 2012). Similarly, Purba and Sipayung (2022) reported that monthly applications of glyphosate for three successive years resulted in glyphosate resistance in *E. indica.* Furthermore, some growers often fail to follow recommended guidelines for herbicide application, increasing the risk of resistance development (Seng et al., 2024). The biology, ecology, lifecycle, and genetics of weeds also contribute to the resistance (Perotti et al., 2020).

In Malaysia, eight weed biotypes have developed herbicide resistance in oil palm nurseries and plantations (Ramadzan et al., 2012; Heap, 2025). The first case of herbicide resistance occurred in 2005 when *E. indica* showed multiple resistance to glyphosate and paraquat (Chuah et al., 2005). Since then, four weed species, *C. odorata*, *C. hirta*, *E. indica,* and *H. verticillata*, have evolved resistance to herbicides like glyphosate, paraquat, metsulfuron-methyl, glufosinate, and fluazifop (Table 1). Notably, all these weeds are considered noxious due to their aggressive growth, intense competition with crops, and resistance to control measures. A recent survey of oil palm plantations in Peninsular Malaysia reported the presence of five putative-resistant biotypes, such as *E. indica*, *C. hirta*, *M. malabathricum*, *Ischaemum muticum* L., and *A. gangetica* (Seng et al., 2024).

Globally, 534 unique cases of herbicide-resistant weeds involving 73 species have been reported in 100 crops in more than 70 countries (Heap, 2025). Presently, herbicide resistance is the principal factor affecting the successful control of weeds. Resistant biotypes threaten agricultural productivity because they can survive herbicide applications, reproduce, spread, and become dominant in weed communities, making weed management difficult. This consequently leads to lower crop yields and an increased cost of weed control (Kurniadie et al., 2023; Ofosu et al., 2023; Seng et al., 2024). Furthermore, the limited herbicide options in oil palm management and the lack of new modes of action make herbicide resistance a concern (Dilipkumar et al., 2020). Hence, implementing effective strategies that reduce the impact of herbicide-resistant weeds is crucial in preventing economic losses and sustaining productivity.

Although several reports have highlighted the negative impact of herbicide-resistant weeds on oil palm productivity (Dilipkumar et al., 2020; Umiyati et al., 2023; Seng et al., 2024), current data on their competitive effects on oil palm yield and quality are limited. Furthermore, there is no documented information regarding the resistance mechanisms of these weeds except for *E. indica*. Focusing on lesser-studied herbicide-resistant weed species is essential for effective crop management and sustaining agricultural productivity. Research should be conducted to quantify the impact of herbicide-resistant weed species on Malaysian oil palm plantations. Investigating the specific mechanisms is important in developing targeted management strategies against these weeds.

Mechanisms of Herbicide Resistance

The mechanisms involved in herbicide resistance are target-site resistance (TSR) and non-target-site resistance (NTSR) mechanisms. TSR in weeds is caused by mutations that alter the target site of the herbicide, thereby reducing its binding affinity for the herbicide. TSR may also be caused by overexpression, which requires a higher herbicide concentration to inhibit the enzyme. While, NTSR involves mechanisms such as reduced absorption and translocation, enhanced metabolism, and rapid detoxification of herbicides that prevent phytotoxic amounts of herbicide from reaching the target site (Murphy & Tranel, 2019). NTSR has been linked to cross-resistance in weeds. This occurs when resistance to one herbicide confers resistance to others with the same mode of action. Weeds can also evolve resistance to multiple herbicides with different modes of action caused by either a mutation or several TSR and NTSR mechanisms (Gaines et al., 2020). Cross-resistance and multiple resistance limit the efficacy of diverse herbicides, making weed control difficult.

In Malaysia, weeds are resistant to five herbicide classes with different modes of action. The following discussion briefly describes resistance to these classes.

Resistance to Groups of Herbicides

Acetyl-CoA Carboxylase (ACCase) Inhibitors

Acetyl-CoA carboxylase (ACCase) inhibitors are herbicides targeting the ACCase enzyme, essential for lipid biosynthesis. This disruption leads to cell membrane damage and, eventually, the death of the plants (Murphy & Tranel, 2019). There are three chemical families in ACCase inhibitors: (1) aryloxyphenoxypropionates (FOPs), (2) cyclohexanediones (DIMs), and (3) phenylpyrazolin (DEN). These herbicides are extensively used to control grasses due to their low soil toxicity and being selective in major crops.

However, resistance to these herbicides has been reported in at least 51 weeds worldwide (Heap, 2025) due to reduced ACCase sensitivity and enhanced metabolism (Perotti et al., 2020). Several studies have identified mutations at seven positions: (1) Ile-1781-Leu/Val, (2) Trp-1999-Ser, (3) Trp-2027-Cys, (4) Ile-2041-Asn/Val, (5) Asp-2078-Gly, (6) Cys-2088-Arg, and (7) Asn-2097-Asp (Cha et al., 2014; Araújo et al., 2023). ACCase-resistant populations are often resistant to multiple ACCase inhibitors, making their control difficult. Enhanced metabolism of herbicides is associated with cytochrome P450 monooxygenases and glutathione-S-transferases. In Malaysian oil palms, resistance to butroxydim, fluazifop-butyl, haloxyfop-methyl, and sethoxydim has been reported in *E. indica* populations (Cha et al., 2014; Jalaludin et al., 2015; Chuah et al., 2023)

Resistance to Acetohydroxyacid Synthase (AHAS) Herbicides

Acetohydroxyacid synthase (AHAS) or acetolactate synthase (ALS) herbicides inhibit the plant enzyme, thereby preventing the synthesis of the branched-chain amino acids, valine, leucine, and isoleucine, ultimately leading to plant death. They consist of six groups: (1) imidazolinones (IMIs), (2) pyrimidinyl benzoates (PTBs), (3) sulfonanilides, (4) sulfonylureas (SUs), (5) triazolinones (SCTs), and (6) triazolopyrimidines (TPs) (Riechers et al., 2024). These herbicides are effective, selective, broad-spectrum inhibitors of several grass and broadleaved weeds, ensuring their worldwide use (Riechers et al., 2024). However, resistance to AHAS herbicides may develop quickly after just a few applications.

The primary resistance mechanisms to AHAS are target site mutation and, to a lesser extent, enhanced herbicide metabolism by cytochrome P450s (CYP450) (Gaines et al., 2020). Target site mutations lead to amino acid substitutions that reduce the herbicide's ability to bind effectively to the AHAS gene. Twenty-nine amino acid substitutions have been identified at nine positions (Ala122, Pro197, Ala205, Phe206, Asp376, Arg377, Trp574, Ser653, and Gly654) in the AHAS genes across several weeds (Gaines et al., 2020; Zakaria et al., 2021; Heap, 2025). Enhanced metabolism by CYP450 enzymes has also been observed in resistant weed species.

Resistance to Glyphosate

Glyphosate is a systemic herbicide that targets 5-enolpyruvylshikimate-3-phosphate synthase (EPSPS), an enzyme essential for the biosynthesis of aromatic amino acids needed for protein synthesis in plants. By inhibiting EPSPS, glyphosate prevents amino acid production, ultimately leading to plant death (Gaines et al., 2020). Glyphosates are used worldwide in several crops. In oil palm plantations, glyphosate has been used for several decades to control weeds due to its efficient control against several weeds (Purba & Sipayung, 2022; Kurniadie et al., 2023). However, the prolonged use resulted in resistance. Currently, glyphosate resistance is the second most reported, with approximately 60 weed species exhibiting resistance worldwide (Heap, 2025).

Various studies have shown that glyphosate resistance in *E. indica* is primarily caused by mutations in the EPSPS gene (Pro106, Pro381, Thr102, Ala103, and Gly 101) and an increased expression of the gene resulting in the overproduction of the EPSPS protein, thereby reducing glyphosate efficacy (Chen et al., 2024; Deng et al., 2022; Kurniadie et al., 2023). Mutations and EPSPS amplification can occur in the same individuals, leading to highly resistant weeds. Enhanced metabolism involving cytochrome P450s and glutathione S-transferases (GSTs), reduced translocation or uptake, or enhanced vacuolar sequestration is the NTSR mechanism (Deng et al., 2022; Chen et al., 2024; He et al., 2024).

Resistance to Glutamine Synthetase Herbicides

Glutamine synthetase herbicides, such as glufosinate ammonium, inhibit glutamine synthetase, a key enzyme catalysing glutamine synthesis from glutamate. This inhibition prevents the conversion of glutamate and ammonia, leading to the accumulation of ammonia and disruption of amino acid metabolism, ultimately leading to plant death, for example, glufosinate-ammonium. Ser59Gly mutation was identified as the resistant mechanism in

E. indica resistant populations from Malaysia and China (Zhang et al., 2022). Resistance may also be conferred by gene amplification/overexpression, leading to increased enzyme activity and reduced sensitivity to the herbicide. Herbicide metabolic resistance to glufosinate involves the activity of the GST genes (Lei et al., 2024).

Resistance to Photosystem I Electron Diverters

Photosystem I (PSI) electron diverters are herbicides that disrupt the photosynthetic process in plants, producing reactive oxygen species that cause the plant's death. This group includes herbicides such as paraquat and diquat (Nazish et al., 2022). These herbicides are nonselective and are used to control weeds in major crops. Resistance to paraquat may be due to the rapid sequestration of paraquat into vacuoles, decreased translocation, and enhanced scavenging of reactive oxygen species (Nazish et al., 2022). In Malaysia*, E. indica* and *H. verticillata,* are resistant to paraquat.

Table 1
Herbicide-resistant weed species in Malaysian oil palm plantations

Weed Species	Common name	Year reported	Mechanism of action	Active ingredient	Location
Hedyotis verticillata	Woody borreria	2005	PS I inhibitors EPSPS Inhibitors	Paraquat Glyphosate	Terengganu
Eleusine indica	Goosegrass	2009	ACCase Inhibitors	Butroxydim Fluazifop-butyl Haloxyfop-methyl	Pahang
			EPSPS Inhibitors	Glyphosate	
			PS I inhibitors	Paraquat	
			Glutamine Synthetase Inhibitors	Glufosinate-ammonium	
Clidemia hirta	Soapbush	2010	AHAS inhibitors	Metsulfuron-methyl	Pahang

AHAS: Aceto Lactate Synthase
ACCase: Acetyl-CoA carboxylase
EPSPS: Enolpyruvyl Shikimate Phosphate Synthase
PS I: Photosystem 1 Electron Diversion

DOCUMENTED CASES AND WEED SPECIES

Hedyotis verticillata (L.) Lam

Hedyotis verticillata (L.) Lam (synonyms; *Oldenlandia verticillata* L.; *Scleromitrion verticillatum* (L.) R. J. Wang), is commonly known as woody borreria. It is a dicot weed in the Rubiaceae family. This perennial weed is native to South and Southeast Asia (POWO, 2024). *H. verticillata* has a sprawling growth habit with stems ranging from 15 to 100 cm. The stem tends to be woody as it matures, making it quite challenging to manage. It is a noxious weed that infests oil palms.

Chuah et al. (2005) identified several herbicides for control, such as paraquat, glyphosate, metsulfuron-methyl, triclopyr, fluroxypyr, 1-methyl heptyl ester, and picloram. However, the use of paraquat has been stopped due to safety concerns for humans and the environment. These herbicides are used with cultural, physical, biological, and mechanical methods.

Hedyotis verticillata first evolved multiple resistance to PS I and EPSPS inhibitors in Malaysia in 2005. This resistance was first detected in the Federal Land Consolidation and Rehabilitation Authority (FELCRA) oil palm plantations in Terengganu, where these herbicides have been used repeatedly for at least three consecutive years. Chuah et al. (2005) attributed herbicide resistance in the population to the same herbicide use, tank mix, and herbicide rotation. *Hedyotis verticillata* showed multiple resistance to glyphosate and paraquat, likely involving both TSR (EPSPS gene mutations) and NTSR mechanisms. It may also be cross-resistant to other EPSPS inhibitors. However, specific studies are needed to confirm this. Limited information on its weed biology, genetics, and current resistance status complicates control efforts.

Using alternative herbicides and diversifying weed control methods could effectively manage the herbicide-resistant weed. Zakaria et al. (2020) demonstrated the efficacy of aqueous leaf extracts of *Murraya koenigii* (L.) Spreng in inhibiting the emergence and growth of *H. verticillata* seedlings. Furthermore, the compound 5-(3-Fluoro-phenyl)-7-methyl-5H-thiazolo[3,2-a]pyrimidine-6-carboxylic acid ethyl ester ("c") showed high post-emergence and pre-emergence herbicidal activity against *O. verticillata* and *E. indica.* The herbicidal action of compound "c" is attributed to its ability to trigger electrolyte leakage in the plant cells, a novel mode of action compared to traditional herbicides (Abdullah et al., 2021). However, further research is needed to develop pre-emergence natural herbicides from these extracts that can help to mitigate resistance in this weed species.

Eleusine indica **L. (Gaertn)**

Introduction

Eleusine indica L. (Gaertn), commonly known as goosegrass, is an annual grass belonging to the Poaceae family. Although native to Africa, it is widespread in other tropical regions (Rojas-Sandoval & Acevedo-Rodríguez, 2014a). It is among the top 10 worst weeds prevalent in over 50 crops in at least 60 countries. *E. indica* has a prostrate or spreading growth, although it can also grow upright, reaching a height of up to 60 cm. The sheaths and stem bases are distinctly flattened. The plant has a tufted base from which culms arise, with each culm bearing an inflorescence. Its green, flat leaves can be up to 8 mm wide and 15 cm long (Rojas-Sandoval & Acevedo-Rodríguez, 2014a).

E. indica has a rapid, continuous life cycle, germinating and producing seeds throughout the year, with multiple generations possible in a single season. A mature plant can produce 50,000 to 140,000 seeds, which are easily spread by wind, water, and animals, creating a large seed bank in the soil, which readily germinate to produce abundant seedlings. Due to its fast growth, aggressiveness, and well-developed root system, it is almost impossible to eradicate once it is established. *E. indica* thrives in moist, fertile soil in full sunlight but can grow in various environmental conditions (Jalaludin et al., 2010). Its tolerance to many herbicides makes it a major concern for farmers.

Herbicide Resistance (Mechanisms and Studies)

In Malaysia, *E. indica*, locally known as "rumput cakar ayam" or "rumput sambau", is prevalent in nurseries of oil palm and rubber, orchards, and vegetable fields, causing a drastic effect on crop yields due to the lack of canopies (Jalaludin et al., 2010). *E. indica* infestation in farms and plantations is normally controlled through herbicide application. Unfortunately, the heavy herbicide use led to its resistance to several herbicides such as glyphosate, glufosinate, paraquat, and fluazifop (Jalaludin et al., 2015; Sim et al., 2020; Purba & Sipayung, 2022). The high variation in the molecular and morphology in *E. indica* may also contribute to this multiple resistance (Saidi et al., 2016).

Resistance to glufosinate ammonium in *E. indica* was first detected in an oil palm nursery in Jerantut, Pahang, in 2009. Further investigation confirmed the high and multiple resistance to paraquat and three ACCase inhibitors (fluazifop-P-butyl, haloxyfop-P-methyl, and butroxydim).

Resistance to glufosinate ammonium in *E. indica* has been studied less than in other herbicides (Zhang et al., 2022). However, enhanced metabolic pathways by GST and other NTSR mechanisms are important in glufosinate resistance in *E. indica* (Lei et al., 2024). Amino acid substitutions at Trp-2027-Cys and Asn-2097-Asp in the ACCase gene contributed to the resistance in *E. indica*, although NTSR mechanisms may also be involved (Cha et al., 2014; Jalaludin et al., 2015). Other mutations such as Trp-1999-Ser, Trp-2027-Cys, and Asp-2078-Gly have been reported in resistant *E. indica* from China, and Asp-2078-Gly in the resistant population from Brazil (Araújo et al., 2023; Deng et al., 2023). Also, some populations demonstrate enhanced metabolism, further complicating management.

Similarly, glyphosate resistance in *E. indica* is linked to mutations in the EPSPS gene and an increased expression of the EPSPS enzyme, reducing the weed's sensitivity to herbicides. A double mutation at Thr102Ille and Pro106Ser (TIPS) was identified in highly resistant plants (Jalalulidin et al., 2015; Zhang et al., 2021). Kurniadie et al. (2023) attributed

Thr102Iso and Pro106Ser amino acid mutations in the EPSPS gene as the mechanisms in glyphosate-resistant *E. indica* from oil palm in Indonesia. Enhanced metabolism involving the ATP-binding cassette transporter, aldo-keto reductase, and CYP genes are associated with NTSR (Deng et al., 2022; Chen et al., 2024; He et al., 2024).

Eleusine indica develops resistance through various TSR and NTSR mechanisms, leading to cross- and multiple resistance. Weeds resistant to glyphosate are often resistant to herbicides such as glufosinate and paraquat, ACCase inhibitors (Jalaludin et al., 2015; Zhang, et al., 2021; Kurnadie et al., 2023; Umiyati et al., 2023). They are also more likely to develop resistance to alternative herbicides, such as protoporphyrinogen oxidase (PPO) and PSII inhibitors, which makes their management challenging.

Management Strategies

Managing resistant *E. indica* involves using alternative herbicides and their mixtures. Herbicide mixture of MSMA+Diuron effectively controlled multiple resistant *E. indica* in young oil palms in Malaysia and Indonesia (Sim et al., 2020; Tampubolon et al., 2020). Several studies have reported the high efficacy of post-application herbicides such as ametryn, glufosinate ammonium, premixed MSMA + diuron, propaquizafop, sulfentrazone, and topramezone in controlling resistant populations (Purba & Sipayung, 2022; Kurniadie et al., 2023). Similarly, pre-application herbicides, including diuron, flumioxazin, indaziflam, oxyfluorfen, and pendimethalin, effectively suppressed glyphosate-resistant *E. indica* populations (Purba & Sipayung, 2022; Tampubolon et al., 2024). Furthermore, a combination of oil palm frond residues and reduced pre-emergence herbicide rates inhibited the emergence and growth of *E. indica* seedlings (Chuah & Lim, 2021).

The concerning levels and patterns of herbicide resistance observed in *E. indica* populations underscore the need to use different herbicides and adopt integrated weed management (IWM) methods, such as cover cropping and livestock grazing.

***Clidemia hirta* (L.) D. Don**

Clidemia hirta (L.) D. Don. (Synonym; *Miconia crenata* (Vahl) Michelang.), commonly known as “Koster’s curse” or soapbush, is a dicot weed belonging to the Melastomataceae family (Ramadzan et al., 2012). *C. hirta* originated from the Caribbean, Central and South America, but is now widely distributed in other tropical regions such as Australia, peninsular Malaysia, East and West Africa, and several oceanic islands.

Biology and Ecology

Clidemia hirta is a densely branched, hairy perennial shrub, between 1 to 5 metres tall. It is supported by shallow lateral roots and abundant fine roots with several stems arising from the rootstalk and the base of the main stem in mature plants. The leaves are about 5–18cm long and are oppositely arranged on slender twigs and branches. They are ovate, with a cordate base and elongated tip having either a serrated or entire margin and five distinct veins radiating from the base. The flowers are white or pink coloured and are grouped in small clusters at the tips of the branches (Rojas-Sandoval & Acevedo-Rodríguez, 2014b).

Clidemia hirta is considered one of the world's worst invasive species, reported in over 50 countries infesting several economic crops (Ramadzan et al., 2012; Rojas-Sandoval & Acevedo-Rodríguez, 2014b). Locally known as "senduduk bulu", *C. hirta* is one of the most noxious weeds competing with the crops for water, light, and nutrients in Malaysian orchards and plantations. Furthermore, it smothers and causes physical stunting of immature palms and reduces fruit yield in mature palms, leading to poor agricultural productivity (Ramadzan et al., 2012). In addition, *C. hirta* has been shown to exhibit antipathogen effects, which may enhance its competitive and invasive ability (Pratami et al., 2021).

The presence of *C. hirta* continues to be a major constraint in plantations due to its broad ecological tolerance, quick spread, prolific seed production (a single plant can produce between 100,000 to 500,000 seeds), lack of natural predators, and inclination to form dense and monotypic thickets (Conant, 2009). *C. hirta* is also shade-tolerant and thrives in mature plantations. These traits enable its survival and continue to spread when introduced into new cropping areas, making *C. hirta* a serious threat to oil palm productivity.

Herbicide Resistance in **C. hirta**

Clidemia hirta was first reported to have acquired resistance to metsulfuron-methyl in 2010, and subsequent experiments further established the resistance (Chuah & Sahid, 2010; Ramadzan et al., 2012). Resistance in *C. hirta* has been attributed to a target-site mutation that reduces the ability of the enzyme to bind effectively to the AHAS gene. Although amino acid substitutions have been reported at nine positions in the AHAS gene, resistance to the SU family is primarily due to changes at Pro197 and Trp574 (Tranel et al., 2025). Enhanced metabolism by the CYP450 enzymes may also be responsible for resistance. This biotype's moderate to high resistance levels indicated a potential cross-resistance to other herbicides in the same chemical family/class (Ramadzan et al., 2012). Given its potential for spread, herbicide-resistant *C. hirta* has likely spread to other areas but is under-recorded.

Effective control of this resistant weed has proven difficult. Mechanical methods are unsuccessful because it resprouts vigorously after being cut. Therefore, control of *C. hirta* mostly depends on fluroxypyr, metsulfuron, triclopyr, picloram, and 2,4-D (Department of Agriculture, Malaysia [DOA], 2025). Using alternative herbicides, rotating them, livestock grazing, and mulching will help prevent the weeds' growth, thereby delaying the onset and reducing the spread of resistant individuals.

Recently, the AHAS gene fragment of susceptible *C. hirta* and the nucleotide sequence (2384bp) comprising the nine potential mutation sites were registered in GenBank (Accession No. PQ153909). However, research on the specific mechanisms of herbicide resistance in *C. hirta* is still lacking. Thus, research elucidating its resistance mechanisms is crucial for weed management decisions.

IMPLICATIONS OF HERBICIDE RESISTANCE

Herbicide resistance in oil palm plantations significantly impacts agricultural productivity and environmental sustainability (Purba & Sipayung, 2022). With weeds becoming resistant, herbicide applications are becoming less effective. This forces managers to rely on alternative control methods, such as more expensive herbicides, frequent applications, and manual and mechanical hand-weeding, thereby increasing management costs (Purba & Sipayung, 2022; Kurniadie et al., 2023; Seng et al., 2024). Given that the recommended herbicides for oil palm plantations are few, resistance limits available options, thereby narrowing viable weed management strategies (Dilipkumar et al., 2020). Some resistant species, like *E. indica*, further resist multiple herbicide groups, limiting herbicide options (Jalaludin et al., 2015; Heap, 2025). The rise of herbicide-resistant weeds complicates integrated weed management (IWM) practices.

Also, herbicide resistance may lead to over-reliance on more toxic herbicides and environmental and health concerns such as food contamination, human health risks, and biodiversity loss (Zakaria et al., 2020; Umar et al., 2023). For instance, the evaluation of oil palm plantation soils in Sepang, Selangor, showed the presence of diuron for up to 90 days after application (Muhamad et al., 2013). Some herbicides, including glyphosate, glufosinate ammonium, fluroxypyr, metsulfuron-methyl, and triclopyr, have also been detected in water bodies, soils, and sediments linked to oil palm plantations (Mardiana-Jansar & Ismail, 2014; Mardiana-Jansar & Ismail, 2016; Tayeb et al., 2017; Dearlove et al., 2024).

Furthermore, herbicides may also destroy non-target understory vegetation vital for supporting biodiversity within oil palm ecosystems (Umar et al., 2023). Long-term use of herbicides harms beneficial soil microorganisms, inhibiting their growth and disrupting the natural balance between pathogens and beneficial organisms (Zain et al., 2013). This consequently impacts microbial activity and soil health. Furthermore, herbicides can make oil palm seedlings more susceptible to diseases like *Ganoderma boninense* by causing wounds that allow pathogen entry, thus compromising crop health (Hussin et al., 2021).

As herbicide-resistant weeds continue to spread, sustainability efforts are undermined. Increased chemical use and harmful practices can prevent plantations from meeting sustainability standards, like the Roundtable on Sustainable Palm Oil (RSPO) and Malaysian Sustainable Palm Oil (MSPO) certifications, which aim to reduce herbicide use (Azhar et al., 2021; Nobilly et al., 2022). The spread of herbicide resistance also poses a significant risk to neighbouring or newly established plantations. Resistant weed populations may contaminate these areas through seed dispersal by wind, water, or human activities. This cross-contamination exacerbates the resistance issue and introduces potential environmental and crop health risks, making management efforts more challenging.

Lastly, herbicide resistance is expected to influence agricultural policies as Malaysia strives towards sustainable agriculture, food security, and environmental conservation. Future strategies are likely to focus on more integrated and sustainable weed management practices such as biological control, molecular biology, and precision agriculture (Perotti et al., 2020; Ofosu et al., 2023). These approaches aim to reduce reliance on chemical herbicides, protect biodiversity, and address the issue of herbicide resistance. Effective management of herbicide resistance requires a strong technological and regulatory framework. This includes stricter regulations on herbicide use, monitoring systems to track resistance trends, and enforcing compliance with sustainable farming practices. Increased government funding could support research in alternative weed control methods, as well as provide subsidies for adopting these practices. Additionally, regulations promoting the use of precision agriculture, such as drones and sensors, can improve herbicide application efficiency, ultimately mitigating resistance development and spread.

MANAGEMENT OF HERBICIDE-RESISTANT WEEDS IN OIL PALM

Weed management is a crucial component of oil palm cultivation, and various approaches are involved. The concerns posed by herbicide resistance have made implementing diverse and effective weed management strategies necessary to ensure the sustainability of oil palm cultivation in Malaysia. Current weed management in oil palm plantations comprises several methods described below.

Mechanical Control

Mechanical methods like chaining, bulldozing, and ploughing control weeds in plantation crops. Manual weeding, such as slashing of woody weeds, hoeing, and hand pulling, reduces the weed cover and prevents fruiting, thereby slowing the growth and spread of the weed. Plant litter decomposition also releases nutrients into the soil, increasing soil fertility. Mechanical weeding is important in clearing established woody plants such as *C. hirta* and *M. malabathricum*. A major advantage of mechanical control is its ability to reduce herbicide use, thereby lowering the risk of herbicide resistance. By minimising herbicide use, mechanical weeding also reduces environmental impact, allowing beneficial organisms to thrive, preserving soil health, and protecting water resources, ultimately contributing to a more balanced and resilient ecosystem (Formaglio et al., 2020; Iddris et al., 2023).

While mechanical methods offer long-term sustainability by reducing reliance on chemicals and improving biodiversity, they are inefficient, labour-intensive, tedious, and weather-dependent, especially in commercial plantations (Dilipkumar et al., 2020; Ruzlan & Ahmad-Hamdani, 2021). Furthermore, the farm labour shortage affects its practicality (Murphy et al., 2021; Parveez et al., 2024). Mechanical weeding does not remove the roots, allowing plants to grow back quickly. Thus, frequent cutting is essential to maintain effective weed control.

Cultural Control

Cultural weed control in oil palm plantations is a long-term strategy that focuses on preventing weed establishment. Leguminous cover crops, such as *Centrosema pubescens* Benth., *Calopogonium mucunoides* Desv., *Mucuna bracteata* DC. Ex Kurz*., Pueraria phaseoloides* (Roxb.) Benth. and *Stylothanthes* reduce weed growth and cover in immature oil palms (Ruzlan & Ahmad-Hamdani, 2021; Nobilly et al., 2022). Cover crops prevent the sprouting and spread of noxious weeds. It also reduces soil erosion and fixes nitrogen, thereby increasing soil fertility. In addition, the remains of cover crops in the soil increase organic matter and may control weeds by releasing allelochemicals, making plantations more resilient against weed infestations. Considering evolving herbicide resistance patterns, this method minimises the need for herbicides, reducing the risk of resistance development.

Several studies reported that different cover crop systems lead to variations in weed communities and oil palm yields, with *Axonopus compressus* (Sw.) P. Beauv. and *M. bracteata*, showing potential for weed suppression (Samedani et al., 2014; Samedani et al., 2015). However, cover crops require regular de-creeping, either manually or by herbicides, to prevent them from smothering plantation crops due to their creeping/climbing behaviour (Dilipkumar et al., 2020). Mulching is another cultural practice in which cut fronds and empty fruit bunches suppress weed growth, recycle nutrients, and prevent leaching (Ruzlan & Ahmad-Hamdani, 2021).

While cover crops and mulching help suppress weed growth, they may not be sufficient to manage all types of weeds, particularly noxious herbicide-resistant ones. Moreover, cultural controls often require significant changes in plantation practices, which can be challenging to implement on a large scale. Investigating the combination of cover crops with other weed management strategies will provide valuable insights into controlling and preventing herbicide resistance.

Biological Control

The integration of livestock such as sheep, goats, and cattle has been reported in weed control in oil palm plantations. Livestock grazing offers economic, environmental, and ecological benefits while meeting sustainability goals. Livestock grazing in palm oil production helps meet sustainability standards such as RSPO by reducing herbicide use (Álvarez et al., 2024). It also reduces labour and weeding costs in oil palm plantations. Álvarez et al. (2024) reported a 60% reduction in weed control costs and a 15% income increase due to cattle integration. Furthermore, reduced herbicide use lowers workers' health risks and minimises environmental contamination (Tohiran et al., 2017). It also maintains the understory vegetation, protecting the oil palm ecosystem's biodiversity (Nobilly et al., 2022; Umar et al., 2023), and animal droppings contribute to soil fertility (Tohiran et al., 2017).

Recently, a targeted goat grazing study conducted in a mature oil palm plantation in Pahang, Malaysia, observed that noxious weeds such as *A. gangetica* and *C. hirta* were effectively cleared (Nobilly et al., 2022). Likewise, Tohiran et al. (2023) reported that multi-species livestock grazing (sheep and goats) effectively controlled the understorey plants in oil palm plantations compared to grazing by a single species. However, livestock grazing in oil palm largely depends on the animal species and density, grazing plans, and duration. Therefore, integration techniques and the stocking density of animals should be evaluated. Grazing alone often fails to provide adequate long-term control; therefore, combining it with other weed management strategies is important in weed control. Further research and proper management practices are essential for broader implementation.

Chemical Control

This is the most widely used method to control weeds in oil palm plantations (Dilipkumar et al., 2020). Once herbicide resistance is detected, the use of that herbicide should be discontinued. Chemical control includes rotating herbicides with different modes of action and tank mixtures (Kurniadie et al., 2023; Tampubolon et al., 2024). This reduces and delays resistance by lessening the selection pressure caused by herbicides with a single mode of action. The plantations must be monitored regularly after herbicide treatments to eradicate seedlings and probable herbicide-resistant weeds using other methods to prevent the spread. Furthermore, choosing herbicides for mixing requires careful consideration, as some combinations can exhibit antagonistic effects (Dilipkumar et al., 2020). Given the limited available herbicide options, research evaluating herbicides and tank mixtures with different sites of action offering a broad spectrum of weed control is important. It is also crucial to prioritise the development of novel herbicides to improve chemical control.

Integrated Weed Management

With herbicide resistance spreading, conventional weed control becomes less effective. Management practices integrating different control measures, such as chemical, cultural, mechanical, and biological methods, are a practical option for controlling resistant weeds in oil palm cultivation. This strategy reduces herbicide selection pressure by minimising herbicide use. The most widely practised IWM method by plantation companies combines herbicide use and cultural practices with or without biological control. A survey of some selected FGV estates in Lepar Utara, Pahang, indicated that IWM methods effectively managed weeds while reducing weeding costs by RM34.00/ha/year (Ruzlan & Ahmad-Hamdani, 2021). This approach also helped to reduce the occurrence of herbicide-resistant weed species, making it a viable long-term strategy. Chuah and Lim (2021) reported that oil palm frond residues could reduce pre-emergence herbicide rates required to inhibit *E. indica* seedling emergence and growth. Herbicide-treated mulch is a viable option for sustainable control. IWM strategies should also include monitoring for early detection of herbicide resistance. Given the heavy reliance on herbicides, there is a strong need for policies that would promote integrated weed management practices.

Bioherbicides

Bioherbicides involve the application of allelochemicals and natural products from plants, microbes, and insects for weed control (Ofosu et al., 2023). They are economical and eco-friendly, reducing herbicide use and environmental pollution (Ismail et al., 2020; Rusli et al., 2022; Ofosu et al., 2023). As herbicide resistance continues to evolve, bioherbicides can be formulated to target specific species without increasing the dependence on chemicals, offering a promising long-term solution for weed control in oil palm plantations.

Several studies have explored the potential of microorganisms to control weeds. Rusli et al. (2022) reported that PH81, a formulation of the fungus *Phoma herbarum*, showed 91.7% and 80% mortality in nursery and field trials against glyphosate-resistant E. indica. PH81 was also compatible with the herbicide diuron. Two fungal pathogens, *Bipolaris bicolour* and *Bipolaris sorokiniana,* have been recommended for their high efficacy against *E. indica* (Ismail et al., 2020; Fakri, 2022). Fakri (2022) reported that combining *B. bicolor* with ametryn enhanced its effectiveness, resulting in a 50%–94% reduction of leaf colour, shoot height, and weight. Furthermore, Norhafizah et al. (2020) investigated the activity of allelochemical 2,4-di-tert-butylphenol (2,4-DTBP) on the emergence of *E. indica*, and *O. verticilla*ta. Results indicated its efficacy at a rate of 2.5 kg ai/ha, comparable to commercial herbicides. Although bioherbicides are crucial in sustainable weed management, their implementation is low due to environmental factors, formulation challenges, toxicity concerns, and cost. Thus, requiring further research.

Emerging Technologies

Emerging technologies are changing agriculture by addressing traditional challenges such as herbicide resistance, environmental contamination, and high operational costs. These include precision agriculture for effective weed control and molecular markers in herbicide resistance detection.

Precision Agriculture

Emerging technologies in precision agriculture, such as global positioning systems (GPS), Geographic Information systems (GIS), sensor technologies, automated weed control systems, drones, satellites, Internet of Things, and robots, have various applications in oil palm plantations. They are useful in real-time monitoring of soil, meteorological conditions, and crops, allowing for efficient use of farm inputs and reducing waste. Using Unmanned Aerial Vehicles (UAVs), such as sensing drones for high-resolution imaging, is crucial for accurately detecting and mapping weed infestations. These high-resolution images help in creating precise weed cover maps. Based on the weed maps, actuation drones spray herbicides only when necessary, significantly minimising use. Ruzlan et al. (2024) reported that the use of UAVs (drones) for weed control in immature oil palm plantations reduced work time by 37%, water use by 91%, and costs of labour by 81% compared to traditional methods.

Furthermore, the adoption of artificial intelligence is crucial in tackling herbicide resistance. High-quality annotated datasets are generated for image recognition and machine learning. These datasets are crucial for training AI models to correctly detect and identify weeds. AI models can predict weed outbreaks and recommend optimal control measures, enhancing crop yields and sustainability. Firmansyah et al. (2022) proposed a machine learning-based system for weed identification and recognition, which could be deployed in real-time on mobile devices. Jopony et al. (2023) also proposed an automated system to classify immature oil palms based on datasets comprising images of young oil palms with noticeable palm circles.

Incorporating these novel technologies with conventional weed management will result in early detection of herbicide resistance and more effective control of herbicide-resistant weed biotypes in Malaysian oil palm plantations. These technologies are promising options for large-scale weed control due to their efficiency, effectiveness, and economic benefits while reducing environmental damage and promoting sustainable agriculture. However, challenges facing the implementation of UAVs and artificial intelligence in weed control are the significant initial costs and the technical expertise needed to set them up. Therefore, further research is important in developing affordable and easily adaptable technologies.

Molecular Biology

Also, omics technologies such as genomics, proteomics, metabolomics, and transcriptomics are important in understanding and identifying molecular mechanisms that endow herbicide resistance in weeds. RNA sequencing gives great insight into the molecular basis of

NTSR, particularly in weeds with limited or no prior genetic information (Gaines et al., 2020). Current research in next-generation sequencing and transcriptomics is important in elucidating the molecular and genetic regulations of NTSR.

Most often, herbicide resistance is only detected after weeds survive applications that previously controlled them. Early detection using molecular markers (DNA, RNA, and protein markers) that can identify resistance genes and allow for quick assessment of multiple resistances is crucial to preventing its spread (Lowe et al., 2024; Milani et al., 2024; Simard et al., 2024). These methods are faster and more cost-effective than traditional lab-based approaches, ensuring targeted strategies for each weed species, thus reducing ineffective herbicides and resistance. Protein biomarkers have been identified for detecting enhanced metabolic resistance to certain herbicides (Lowe et al., 2024). Enzymes, such as CYP450s, GSTs, and ABC transporters, can also be used as molecular markers in NTSR. The incorporation of omics is crucial for a better understanding of weeds and for improving weed management strategies in the future.

CONCLUSION

The heavy reliance on herbicides for weed control in oil palm plantations has led to the emergence of herbicide resistance in Malaysia. The incidence of herbicide-resistant weeds is increasing due to the insufficient implementation of diverse weed control practices. Inaction in addressing this issue in oil palm plantations may result in serious consequences such as decreased fruit yields, higher operational costs, challenges in effective integrated weed management, environmental contamination, and loss of biodiversity.

Adopting a comprehensive, long-term strategy that addresses current issues and protects the environment while ensuring sustained crop productivity to tackle herbicide resistance is essential. This should integrate sustainable practices, proactive research, innovative technologies, and policies that anticipate future threats to agriculture. Plantation managers should adopt sustainable practices, such as integrated weed management and efficient use of farm inputs, to maintain the overall health and productivity of oil palm plantations. This proactive approach allows timely adjustments to weed management strategies, ensuring their effectiveness. Integrating various practices such as cover cropping, mulching, livestock grazing, the use of alternative herbicides and their mixtures, and the yearly rotation of herbicides helps to reduce the selection pressure on weeds. Weed monitoring to eradicate noxious weeds before they fruit should be conducted regularly to prevent the establishment of such weeds. Training programs on proper herbicide use and integrated weed management can address limited knowledge about herbicide classification and resistance management. Herbicide stewardship should be followed strictly.

Prioritising research and innovation will reduce the onset and spread of herbicide resistance. An extensive understanding of the biology of weed species would provide valuable insights for developing effective controls to reduce the spread of herbicide-resistant weeds. Studies quantifying the competitive effects of lesser-studied weeds and confirming putative resistance are important. Furthermore, there is a pressing need for continued research into herbicide resistance mechanisms as this will help to develop targeted control measures. Future studies focusing on developing rapid diagnostic tests using molecular markers for resistance detection and artificial intelligence (AI) in weed control are crucial in mitigating herbicide resistance.

Science-based policy recommendations, such as those endorsed by the RSPO and MSPO, are important in tackling resistance by minimising herbicide use. Regulations regarding sustainable practices should be monitored to ensure compliance. Equally important is the collaboration of all stakeholders in integrating various management strategies.

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