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# Comparative Evaluation of Manual and Herbicide-Based Weed Control in the Immature Oil Palm Phase

Heru Wansyah Harahap[1,✉], Hartini[1]

[1] Polytechnic LPP Yogyakarta, INDONESIA.

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Corresponding Author:
✉ herwansyahharahap@gmail.com
(Heru Wansyah Harahap)

**ABSTRACT**

*Weeds become major constraint in oil palm plantations as they compete for nutrients, light, and water, thereby extending the non-productive period. This study aimed to evaluate the effectiveness of weed control methods on the dominant weed species in the immature oil palm plants (TBM). The research was conducted at Johan Sentosa Estate, PT Agrinas Palma Nusantara, using a Randomized Block Design with three treatments and 10 replications. The treatments involved A (450 mL/ha glyphosate + 22.7 g/ha metsulfuron-methyl), B (manual weeding), and C (450 mL/ha paraquat + 22.7 g/ha metsulfuron-methyl). Observation included weed mortality, regrowth, phytotoxicity, and operational cost. Data was analyzed using Kruskal–Wallis and Mann–Whitney tests at a 5% significance level. Results showed significant differences among treatments ($p < 0.05$) with manual weeding (B) achieved the highest weed mortality in the early observation (mean rank = 15.50) but incurred the highest annual cost 589,621.45 IDR/ha. Treatmant A provided the most effective suppression of weed regrowth up to the 8$^{th}$ week (mean rank = 15.50) with annual cost 355,056.61 IDR/ha, and treatment C showed comparable effectiveness to A but a lower cost 339,397.25 IDR/ha. None of the treatments caused phytotoxicity symptoms (score 0) on oil palm plants. The treatment A using glyphosate and metsulfuron-methyl was identified as the most effective and cost-efficient weed control method for immature oil palm circles.*

## 1. INTRODUCTION

Plantations are one of the supporting sectors of the Indonesian economy. The country's foreign exchange earnings from the plantation subsector reached US$33.78 billion in 2023, of which 70.85% came from oil palm plantations (Kementerian Pertanian, 2024). Oil palm plantations in Indonesia continue to grow over time, as evidenced by the increasing area of oil palm plantations, reaching 16.83 million hectares by 2023, with the main centers located on the islands of Sumatra and Kalimantan. Based on ownership, oil palm plantations in Indonesia are divided into three groups: large state-owned plantations, large private plantations, and smallholder plantations (Haryanti & Marsono, 2021). In addition to being a major source of national income, oil palm plantations also employ more than 17 million workers, both directly and indirectly. Therefore, oil palm plantations have significant potential for national economic stability, especially in oil palm plantation centers.

Despite their significant role in the national economy, productivity of CPO (crude palm oil) and PKO (palm kernel oil) which previously reached 54.84 million tons experienced a decline in 2024 to 52.76 million tons, or a decrease by 3.80% (GAPKI, 2025). This decline indicates challenges in maintaining plantation productivity, one of which is related to the effectiveness of maintenance activities. In this context, maintenance costs are a key factor in the sustainability of oil palm plantations, with weed control being a major component. Various studies have shown that costs for weed control ranks second after fertilization in oil palm maintenance, especially during the immature plant

(TBM) phase until the early production period (Bin *et al*., 2021). This finding is also strengthened by Arbania *et al*. (2021), who stated that weed control is the largest maintenance and care cost for oil palms after fertilization. These costs include components of herbicide use, manual labor, and mechanical maintenance. All components are aimed at minimizing weed competition with the main crop for nutrients, light, and water. Therefore, weed management is a crucial pillar in the overall strategy to improve the cost efficiency and productivity of oil palm plantations.

Weed management in oil palm plantations can be carried out manually, technical culture, or chemical methods. However, these methods often face limitations such as inconsistent application efficiency and potential weed resistance to herbicides (Bilkis *et al*., 2022). The most promising solution for weed control in oil palm plantations is the weed control based on Integrated Weed Management (IWM). This approach combines herbicide and non-chemical (manual, mechanical, mulching, cover cropping) control to reduce labor costs and herbicide requirements while maintaining ecosystem functions. The main drawbacks is that the dependence on herbicides triggers the emergence of weed resistance, while manual methods are often less efficient at plantation scale and sensitive to labor availability, thus requiring site-specific adaptation and further research for long-term cost-benefit optimization (Kaur *et al*., 2024).

Previous research found that the recommended dose for weed control in oil palms during the productive phase (TM) was 1.0 L/ha of isopropylamine glyphosate and 6.67 g/ha of metsulfuron-methyl (Mahmud *et al*., 2025). Meanwhile, the use of herbicide paraquat dichloride at the recommended dose of 552 g/ha proved effective in suppressing the growth of various weeds, such as *Ottochloa nodosa*, *Paspalum conjugatum*, and *Asystasia gangetica*, and is able to significantly control total weed growth with results equivalent to manual weeding (Sari & Pujisiswanto, 2024). However, the combination of paraquat and metsulfuron-methyl herbicides did not show a significant interaction in increasing the effectiveness to control weed *Dicranopteris linearis* in the oil palm of TM phase (Seda, 2022), so it is necessary to conduct other experiments on oil palm plants with the TBM and different dominant weed types.

The herbicide glyphosate works systemically by inhibiting the enzyme EPSPS (5-enolpyruvylshikimate-3-phosphate synthase) in the shikimate pathway, thereby disrupting the synthesis of aromatic amino acids and causing plant death after translocation to the growing point (Singh et al., 2020). In contrast, paraquat is contact herbicide, acting as a false electron acceptor in Photosystem I and producing reactive oxygen radicals (ROS) that damage cell membranes and chlorophyll, causing fast "knock-down" effect (Silva et al., 2024). Meanwhile, metsulfuron-methyl, a systemic herbicide of the sulfonylurea group, inhibits the ALS (Acetolactate Synthase) enzyme, interferes with the synthesis of essential amino acids (Tang et al., 2021). The combination of glyphosate and metsulfuron represents a dual systemic system with broad spectrum and long-term control, while paraquat and metsulfuron combine a rapid contact effect with systemic residual action. Both combinations illustrate two distinct mechanisms, systemic versus contact, that are relevant for testing on weed species and growth stages of TBM to determine optimal effectiveness.

Although the use of herbicides such as glyphosate, paraquat, and metsulfuron has been widely implemented in oil palm plantations, quantitative information on the effectiveness and cost-efficiency of systemic (glyphosate + metsulfuron) and contact (paraquat + metsulfuron) herbicide combinations for oil palm discs in the TBM phase is still very limited. This condition creates a research gap in determining the most effective, efficient, and appropriate herbicide formulations for controlling the dominant weed composition in the TBM phase. Therefore, this study aims to comparatively evaluate the effectiveness of manual and herbicide-based weed control on immature oil palm (TBM) tree discs to determine the most optimal control method for suppressing weed growth, based on a cost evaluation of each method. The results of this study are expected to provide a scientific basis for the implementation of sustainable weed control strategies, support efficient plantation maintenance, and contribute to increasing productivity and the economic sustainability of oil palm plantations.

## 2. RESEARCH MATERIALS AND METHODS

### 2.1. Research Site and Materials

Research was performed in two stages, namely weed vegetation analysis and weed controlling application. This research was conducted at PT. Agrinas Palma Nusantra, Johan Sentosa Plantation located in Sei Jernih, Pasir Sialang Village, Bangkinang Kota District, Kampar Regency, Riau. Johan Sentosa Plantation has coordinates around 0°25'38.56" N, 100°55'12.95" E with Inceptisol soil type. It has a tropical climate with an average maximum temperature of 32–33 °C, average annual rainfall >2000 mm, annual rainy days ranging between 112–182 days, average annual air humidity ranging between 82.3%, has an altitude of <500 meters above sea level with flat, gently sloping and undulating land topography, and had a relatively high weed infestation rate. The immature plant (TBM) age was 28 months with an area of >1,000 ha.

### 2.2. Weed Vegetation Analysis

Weed vegetation analysis was conducted in five blocks of immature oil palm plantation (TBM), namely blocks C22, C23, B23, B24, and A24. These blocks were chosen purposively by considering the criteria that the blocks had rapid weed growth due to favorable conditions for weed development and that the blocks had entered the weed control rotation. Weed vegetation analysis was conducted using a square of 1 m × 1 m by identifying weed composition and density. Each block consisted 25 sample trees, resulting in a total of 125 sample trees. This method is commonly used because is relatively fast, easy, and accurate for determining the composition, density, and dominance of weeds in a location. The recorded data (weed composition and density) was then used to analyze weed vegetation characteristic including relative density (*KN*), relative frequency (*FN*), Summed Dominance Ratio (*SDR*), and Importance Value Index (INP). The calculation was performed using formulas adopted by Ramlan *et al*. (2019) as the following:

$$\mathrm{KN} = \frac{\text{absolute density of a species A}}{\Sigma \text{ absolute density of all species}} \times 100\% \tag{1}$$

$$\mathrm{FN} = \frac{\text{absolute frequency of a species A}}{\Sigma \text{ absolute frequency of all species}} \times 100\% \tag{2}$$

$$\mathrm{INP} = \mathrm{KN} + \mathrm{FN} \tag{3}$$

$$\mathrm{SDR} = \frac{\mathrm{KN} + \mathrm{FN}}{2} \times 100\% = \mathrm{INP}/2 \tag{4}$$

where absolute density of a species is the total number of weed individuals of a species per unit area of the sample plots, and absolute density of all species is the total number of individuals of all weed species per unit area of the plots. Whereas, absolute frequency of a species is the number of sample plots where a weed species appears divided by the total number of observation plots, and absolute frequency of all species is the sum of all absolute frequency values of all weed species.

### 2.3. Weed Controlling Application

This study used a quantitative method with a Randomized Block Design consisting of three treatment levels and ten replications for each treatment. The treatments included: M1 (application of glyphosate herbicide + metsulfuron methyl), M2 (manual weeding), and M3 (application of paraquat herbicide + metsulfuron methyl). Each treatment was repeated ten times to produce thirty tress as experimental unit.

Location block for weed treatment application was determined based on the results of the calculation on weed characteristic. In this case, the application for were controlling method was conducted in block C22. Based on the weed vegetation analysis, block C22 had relatively high level of weed dominance. The study was conducted by taking three harvesting paths or collection point, each consisting of ten oil palm trees, resulting in a total of 30 sample trees as experimental units. Each experimental unit had a plot size in the form of a disc with a diameter of two meters around the oil palm tree. Each sample tree disc was created in the same size to record and count all weed species growing within it (Nduru *et al*., 2023). Sample trees were selected purposively by taking into account the uniformity of plant conditions and topography in the plantation area.

#### 2.1.1. Application of Treatment

The tools in this study included machetes used to manually clear weeds around the oil palm tree disc and knapsack sprayers. Main materials included metsulfuron-methyl 20 WP, systemic herbicide Isopropylamine Glyphosate 486 g/L equivalent to Glyphosate 360 g/L, and contact herbicide paraquat dichloride 276 g/L. For both herbicides, a solution concentration of 5 mL/L of water was prepared. For metafuron-methyl used a concentration of 0.25 g/L water.

Treatments were applied to predetermined sample trees and marked with stakes according to the treatment. Herbicide application was carried out using a 15-L electric knapsack sprayer with a VLV200 nozzle at a working pressure of 1 kg/cm². Spraying was carried out at a height of 60 cm from the ground surface with a spray width of 1.2 m. Calibration was carried out using the area method, obtaining a flow rate of 0.92 L/min with a spray volume of 200 L/ha. Manual treatment was carried out by clearing weeds in the experimental tree disc until clean using a machete locally called *ombang-ambing*. Each treatment was carried out at around 07:00 in the morning during sunny conditions to ensure effective herbicide absorption and minimize evaporation of the spray solution. The herbicide dosage was made according to the standard operating procedures with a dosage of glyphosate (450 mL/ha), metsulfuron-methyl (22.7 g/ha), and paraquat (450 mL/ha).

#### 2.1.2. Observation

Observations of weed mortality rates were conducted periodically from 1 week after application (WAA) to 3 WAP to determine the weed response to the treatment. Weed mortality rates were assessed visually on the tree disc area, referring to the weed mortality scoring criteria as proposed by Situmorang *et al.* (2023) as shown in Table 1. Each scoring category reflects the morphological condition of the leaves, ranging from fresh green to dry and dead. Therefore, observation did not use a calculation of weed mortality percentages, but was based on visual scores that describe the gradual and objective level of weed mortality.

Table 1. Scoring of weed mortality levels (Situmorang *et al*., 2023)

| Weed Mortality Rate | Score |
|---|---|
| Fresh green leaves | 1 |
| Yellowish green leaves | 2 |
| The leaves are yellow and starting to dry out. | 3 |
| Dried leaves | 4 |
| Dry and dead leaves | 5 |

Table 2. Scoring of weed regrowth rate (EWRC, 1964)

| Weed regrowth | Score |
|---|---|
| No visible herbicide effect, 100% normal weed regrowth | 0 |
| Very few symptoms of damage, 90-99% normal weed regrowth | 1 |
| Symptoms of damage are mild but clearly visible, weed regrowth is 80-89% normal | 2 |
| Symptoms of damage are more obvious but not continuous, Weed regrowth is 70-79% normal | 3 |
| Symptoms of severe damage but some weeds recovered, Weed regrowth 60-69% normal | 4 |
| Heavy damage, some weeds dead, Weed regrowth 50-59% normal | 5 |
| Very heavy damage, many weeds died, weed regrowth 40-49% normal | 6 |
| Only a few weeds survived, Weed regrowth 30-39% is normal | 7 |
| Very few weeds survive, Weed regrowth 10-29% is normal | 8 |
| All weeds dead, No weed regrowth (0-9% normal) | 9 |

Weed regrowth rates were observed to assess the ability of weeds to regrow after control measures were applied to the immature oil palm tree (TBM) discs. Observations were conducted periodically from the 6–8 WAA to obtain a consistent picture of the dynamics of weed regrowth. Weed regrowth data was obtained through visual assessment on the percentage of weed cover on the tree disc using a 0–9 scale developed by European Weed Research Council (EWRC) as summarized in Table 2. This scale was chosen because it provides objective, standardized, and easily applied measurements in the field to evaluate the effectiveness of herbicide control on weed regeneration capacity (Ahmal *et al*., 2025). The assessment in the 8 WAA was used as the final indicator of treatment effectiveness, because during this period weeds that have the ability to survive generally have shown a stable or permanent regrowth phase, so that the observation results reflect the actual recovery capacity of the weed population after control.

Further phytotoxicity observations on the main plants were conducted one WAA and continued for 8 WAA. Assessment of toxicity levels was based on the guidelines from the Direktorat Pupuk dan Pestisida (2012) about

Standard Methods for Herbicide Efficacy Testing with the scoring system in Table 3. Finally, cost evaluation was carried out based on all the equipment and material requirements as well as the labor costs required in accordance with the operational standards of the Johan Sentosa Plantation.

Table 3. Scoring of phytotoxicity levels

| Phytotoxicity Level | Score |
|---|---|
| There is no poisoning, 0-5% of the shape and/or color of the leaves of the oil palm plant growth is abnormal. | 0 |
| Mild poisoning, >5-20% abnormal shape and/or color of leaves or growth of coconut palm | 1 |
| Moderate poisoning, >20-50% abnormal shape and/or color of leaves or growth of oil palm | 2 |
| Severe poisoning, >50-75% abnormal shape and/or color of leaves and/or growth of oil palm | 3 |
| Very severe poisoning, >75% of the shape and/or color of the leaves and/or growth of the oil palm are abnormal. | 4 |

Source: Direktorat Pupuk dan Pestisida (2012)

### 2.1.3. Data on Weed Mortality Rate, Weed Regrowth Rate, Phytotoxicity, Weed Regrowth, Cost

The research data includes four main components: weed mortality rate, weed regrowth rate, phytotoxicity to the main crop, and evaluation of treatment operational costs per hectare per year. Mortality assessment was conducted visually using a scoring system based on the level of weed mortality in the crop disk area, referring to general assessment criteria in herbicide efficacy tests. Observations of weed regrowth rate were conducted on the last day of the eighth week or 56 days after application (DAP) to obtain a consistent picture of the ability of weeds to regrow after control, thus assessing the long-term effectiveness of the treatment. Phytotoxicity of oil palm plants was observed visually using a scale of 0–4 according to guidelines Direktorat Pupuk dan Pestisida (2012), to assess the level of poisoning symptoms in the main plants due to herbicide application. Meanwhile, operational cost components are calculated based on three main elements: labor, materials (herbicides), and equipment used during control activities. Labor costs are calculated based on the number of workdays (HK) per control rotation, while material and equipment costs are converted based on actual field usage, including the use of knapsack sprayers for chemical treatment and machetes for manual control. All cost data is based on the company's secondary data.

### 2.1.4. Data Analysis

The research data were analyzed using the non-parametric Kruskal–Wallis test because the scoring data were ordinal and not normally distributed. This test was used to determine significant differences between treatments at the 5% level ($p < 0.05$). If significant differences were found, the Mann–Whitney test was used to compare specific treatment pairs. Data analysis was carried out using IBM SPSS Statistics 26.0 for statistical tests and Microsoft Excel for initial data processing, such as recapitulation of score values, calculation of averages, and presentation of observation results graphs. The analysis was carried out without arcsin√x transformation, because the data processed were not in the form of percentages, but rather visual scoring of the results of observations of the level of weed death, the level of weed regrowth, the level of phytotoxicity in the main crops, and the cost evaluation of each treatment.

## 3. RESULTS AND DISCUSSION

### 3.1. Weed Vegetation Analysis

Table 4 shows results of weed characteristic from the five observation blocks (C22, C23, B23, B24, and A24). The table summarizes the values of weed parameters, including relative density (KN), relative frequency (FN), Summed Dominance Ratio (SDR), and Important Value Index (INP). Based on the results of weed vegetation analysis, block C22 showed the highest level of weed dominance compared to the other blocks. In this block, the most dominant weed species was *Paspalum conjugatum* and *Asystasia gangetica*, each of which has SDR values of 15.56% and 12.56%, and INP values of 31.13% and 25.13%. Both types of weeds were found consistently in all observation blocks with high relative dominance values, thus indicating strong adaptability and competition in the oil palm disc environment in the TBM phase. Therefore, block C22 was designated as the location for implementing weed control treatments because it represents an area with the highest level of weed infestation and an even distribution of dominant species.

Table 4. Results of weed vegetation analysis (KN, FN, SDR, and INP) from five observation blocks

| Weed Name* | KN (%) | | | | | FN (%) | | | | | SDR (%) | | | | | INP (%) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | C22 | C23 | B23 | B24 | A24 | C22 | C23 | B23 | B24 | A24 | C22 | C23 | B23 | B24 | A24 | C22 | C23 | B23 | B24 | A24 |
| *Elaeis guineensis*† | 5.08 | 5.16 | 5.89 | 1.95 | 1.95 | 7.35 | 5.19 | 6.94 | 4.94 | 4.94 | 6.22 | 5.18 | 6.42 | 3.44 | 3.44 | 12.43 | 10.35 | 12.83 | 6.89 | 6.89 |
| *Paspalum conjugatum* | 23.78 | 12.47 | 15.49 | 15.51 | 15.51 | 7.35 | 6.49 | 6.94 | 6.17 | 6.17 | 15.56 | 9.48 | 11.22 | 10.84 | 10.84 | 31.13 | 18.96 | 22.43 | 21.68 | 21.68 |
| *Asystasia gangetica* | 16.24 | 10.33 | 10.91 | 10.59 | 10.59 | 7.35 | 6.49 | 6.94 | 6.17 | 6.17 | 11.79 | 8.41 | 8.93 | 8.38 | 8.38 | 23.59 | 16.82 | 17.85 | 16.76 | 16.76 |
| *Boreraria leavis* | 6.2 | 6.25 | 5.8 | 6.79 | 6.79 | 5.88 | 5.19 | 6.94 | 4.94 | 4.94 | 6.04 | 5.72 | 6.37 | 5.86 | 5.86 | 12.08 | 11.44 | 12.74 | 11.73 | 11.73 |
| *Passiflora foetida L.* | 1.48 | 1.65 | 2.21 | 3.6 | 3.6 | 4.41 | 3.9 | 4.17 | 4.94 | 4.94 | 2.95 | 2.77 | 3.19 | 4.27 | 4.27 | 5.89 | 5.55 | 6.38 | 8.54 | 8.54 |
| *Nephrolepis abrupta* | 5.76 | 4.53 | 2.76 | 5.14 | 5.14 | 4.41 | 6.49 | 2.78 | 6.17 | 6.17 | 5.09 | 5.51 | 2.77 | 5.65 | 5.65 | 10.17 | 11.02 | 5.54 | 11.31 | 11.31 |
| *Nephrolepis exalta* | 2.86 | 5.12 | 3.95 | 3.66 | 3.66 | 4.41 | 5.19 | 4.17 | 6.17 | 6.17 | 3.64 | 5.16 | 4.06 | 4.92 | 4.92 | 7.27 | 10.31 | 8.12 | 9.83 | 9.83 |
| *Centrosema plumierri* | 1.84 | 4.94 | 7.05 | 2.81 | 2.81 | 2.94 | 6.49 | 6.94 | 3.7 | 3.7 | 2.39 | 5.72 | 7 | 3.26 | 3.26 | 4.78 | 11.43 | 13.99 | 6.51 | 6.51 |
| *Clotaria naragutensis* | 1.72 | 2.25 | 1.32 | 6.73 | 6.73 | 2.94 | 2.6 | 2.78 | 6.17 | 6.17 | 2.33 | 2.42 | 2.05 | 6.45 | 6.45 | 4.66 | 4.85 | 4.1 | 12.9 | 12.9 |
| *Teucrium hyrcanicum* | 0.52 | 5.16 | 5.22 | 3.13 | 3.13 | 2.94 | 5.19 | 6.94 | 4.94 | 4.94 | 1.73 | 5.18 | 6.08 | 4.03 | 4.03 | 3.46 | 10.35 | 12.16 | 8.07 | 8.07 |
| *Conyza canadensis* | 0.38 | 3.54 | 0.55 | 1.28 | 1.28 | 4.41 | 3.9 | 1.39 | 2.47 | 2.47 | 2.4 | 3.72 | 0.97 | 1.87 | 1.87 | 4.79 | 7.44 | 1.94 | 3.75 | 3.75 |
| *Gentiana ascleopiadeae* | 0.62 | 0.75 | 1.05 | 3.97 | 3.97 | 2.94 | 1.3 | 2.78 | 4.94 | 4.94 | 1.78 | 1.03 | 1.91 | 4.46 | 4.46 | 3.56 | 2.05 | 3.83 | 8.91 | 8.91 |
| *Male Setaria* | 12.2 | 10.91 | 9.51 | 8.87 | 8.87 | 7.35 | 6.49 | 6.94 | 6.17 | 6.17 | 9.78 | 8.7 | 8.23 | 7.52 | 7.52 | 19.55 | 17.4 | 16.45 | 15.04 | 15.04 |
| *Phillantus nirruri* | 2.86 | 3 | 0.75 | 1.44 | 1.44 | 4.41 | 3.9 | 1.39 | 2.47 | 2.47 | 3.64 | 3.45 | 1.07 | 1.95 | 1.95 | 7.27 | 6.9 | 2.14 | 3.91 | 3.91 |
| *Spigelia anthelmia* | 1.72 | 5.19 | 3.7 | 5.1 | 5.1 | 2.94 | 6.49 | 4.17 | 4.94 | 4.94 | 2.33 | 5.84 | 3.93 | 5.02 | 5.02 | 4.66 | 11.68 | 7.87 | 10.04 | 10.04 |
| *Cylindrical Imperata* | 0.54 | 0.2 | 0.73 | 0.18 | 0.18 | 4.41 | 1.3 | 2.78 | 1.23 | 1.23 | 2.48 | 0.75 | 1.75 | 0.71 | 0.71 | 4.95 | 1.5 | 3.51 | 1.41 | 1.41 |
| *Cerastium semidecandrum* | 4.64 | 4.58 | 6.57 | 3.35 | 3.35 | 7.35 | 6.49 | 6.94 | 4.94 | 4.94 | 6 | 5.54 | 6.76 | 4.14 | 4.14 | 11.99 | 11.07 | 13.51 | 8.29 | 8.29 |
| *Digitaria adscendens* | 5.18 | 6.85 | 5.07 | 5.16 | 5.16 | 4.41 | 6.49 | 6.94 | 4.94 | 4.94 | 4.8 | 6.67 | 6 | 5.05 | 5.05 | 9.59 | 13.34 | 12.01 | 10.1 | 10.1 |
| *Elausina indicates* | 2.62 | 4.28 | 2.74 | 3.72 | 3.72 | 4.41 | 3.9 | 2.78 | 3.7 | 3.7 | 3.52 | 4.09 | 2.76 | 3.71 | 3.71 | 7.03 | 8.18 | 5.52 | 7.42 | 7.42 |
| *Paspalum commersonii* | 3.56 | 1.89 | 7.96 | 4.23 | 4.23 | 5.88 | 3.9 | 6.94 | 3.7 | 3.7 | 4.72 | 2.89 | 7.45 | 3.97 | 3.97 | 9.44 | 5.79 | 14.9 | 7.93 | 7.93 |
| *Stenochlaena palustris* | 0.22 | 0.95 | 0.78 | 2.81 | 2.81 | 1.47 | 2.6 | 1.39 | 6.17 | 6.17 | 0.85 | 1.77 | 1.08 | 4.49 | 4.49 | 1.69 | 3.55 | 2.17 | 8.98 | 8.98 |

Note: *) Local names are as the following

*Elaeis guineensis = kelapa sawit (tunas liar)*
*Paspalum conjugatum = rumput paitan, jukut pahit*
*Asystasia gangetica = rumput israel*
*Boreraria leavis = rumput mutiara*
*Passiflora foetida L. = markisa hutan*
*Nephrolepis abrupta = paku pedang liar*
*Nephrolepis exalta = paku pedang*
*Centrosema plumierri = kacangan centro*
*Clotaria naragutensis = orok-orok*
*Teucrium hyrcanicum = senggugu liar*
*Conyza canadensis = rumput ekor kuda*
*Gentiana ascleopiadeae = gentian biru*
*Male setaria = rumput ekor kucing*
*Phillantus nirruri = meniran*
*Spigelia anthelmia = rumput cacing*
*Cylindrical Imperata = alang-alang*
*Cerastium semidecandrum = rumput bintang*
*Digitaria adscendens = rumput jari*
*Elausina indicates = rumput belulang*
*Paspalum commersonii = rumput paspal*
*Stenochlaena palustris = paku miding/kelakai*

†) refers to the oil palm shoots that grow wild around the main tree.

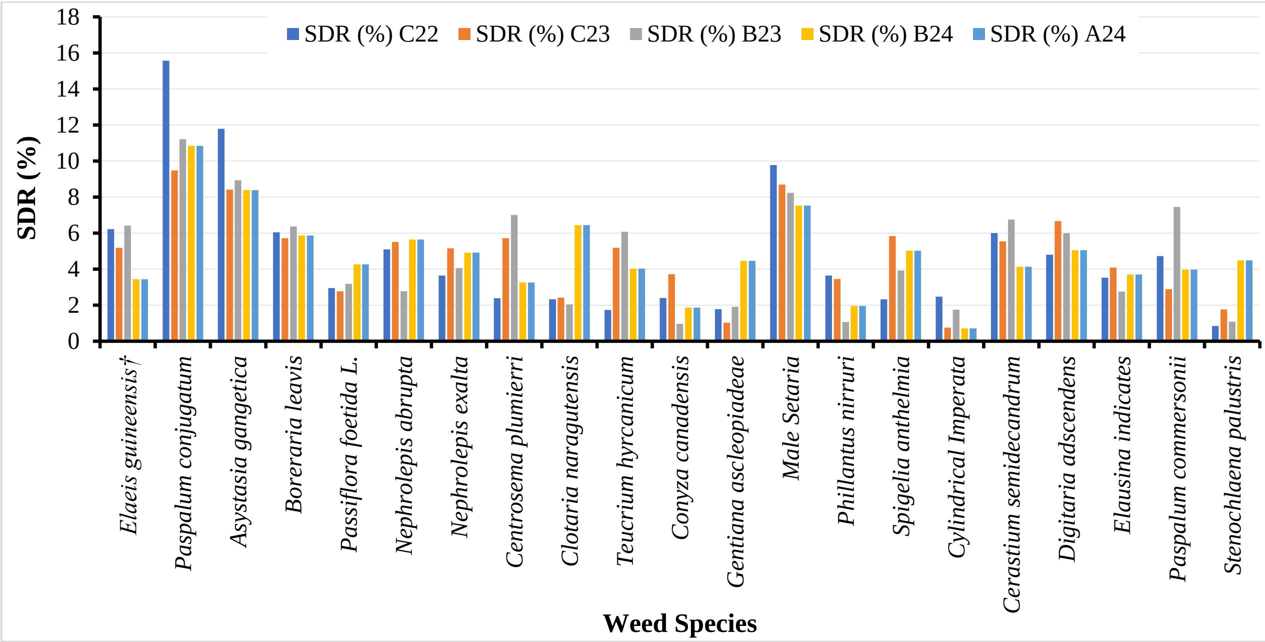


Figure 1. Average SDR value of weed vegetation in five observation blocks

Based on the weed vegetation data analysis in five observation blocks, 21 types of weeds were recorded with varying dominance as depicted in Figure 1. The most dominant types were *Paspalaum conjugatum* and *Asystasia gangetica* with average SDR value of 11.0% and 9.5%, respectively. Next, *Setaria barbata* with SDR value of 8.0%, *Borrerraria leavis* (6.5%), and wild oil palm shoots (6.0%). Weeds with moderate dominance included *Cerastium semidecandrum* (5.5%), *Digitaria adscendens* (5.0%), *Paspalum commersoni* (4.8%), *Nephrolepis exaltata* (4.5%), and *Centrosema plumierii* (4.2%). Other species such as *Spigelia anthelmia*, *Teucrium hircanicum*, *Clotaria naragutensis*, and *Nephrolepis abrupta* each had SDR of 4.0%, while *Eleusine indica* (3.5%) and *Passiflora foetida* (3.0%) were categorized as relatively low dominance levels. Meanwhile, *Gentiana ascleopiadae*, *Conyza canadensis*, *Phillantus niruri*, and *Stenochlaena palustris* each showed an SDR of 2.5%, and *Imperata cylindrica* had the lowest dominance at 1.5%, although it still has the potential to disrupt oil palm growth.

### 3.2. Weed Mortality Rate

Figure 2 shows the trend in weed mortality rates for each treatment. In treatment A, weed mortality was not yet apparent in the first week, but began to increase in the second week and reached full weed mortality by the third week. In treatment B, weed mortality rates were high from the first week, indicating that the manual method proved highly effective in suppressing weed growth from the outset. Meanwhile, treatment C demonstrated relatively stable effectiveness from the first to the second week, with a maximum increase in the third week when weed mortality reached full weed mortality. These results confirm a clear difference in effectiveness between treatments in controlling weeds over time.

Based on the Kruskal–Wallis test results in Table 5, weed mortality rates in weeks 1 and 2 showed significant differences between treatments ($p < 0.05$), while there was no significant difference in week 3 ($p > 0.05$). Therefore, a further Mann–Whitney test was conducted only in weeks 1 and 2 to determine which treatments were significantly different. The results of the Mann–Whitney further test in Table 6 show that weed control effectiveness is significantly different between treatments in the first and second weeks. In the first week, manual treatment (B) had the highest mean rank value and was significantly different from the glyphosate + metsulfuron (A) and paraquat + metsulfuron (C) treatments, indicating that manual weeding was more effective in suppressing weed growth at the beginning of the observation. Treatment C (paraquat + metsulfuron) also showed higher effectiveness than treatment A, indicating that the weed response to paraquat was faster than glyphosate in the initial phase. However, in the second week, although

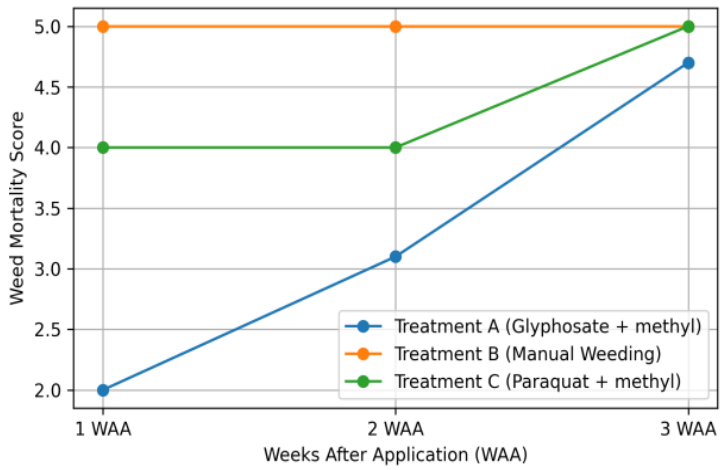


Figure 2. Trend of weed mortality rate

Table 5. Results of the Kruskal Wallis Test on Weed Mortality Rate

| Observation Week | H Statistical Value (Chi-Square) | df | *p*-value (Asymp. Sig.) | Remark |
|---|---|---|---|---|
| Week 1 (1 MSA) | 29 | 2 | 0.00 | Significantly different between treatments |
| Week 2 (2 MSA) | 29 | 2 | 0.00 | Significantly different between treatments |
| Week 3 (3 MSA) | 0 | 2 | 1.00 | No significant difference between treatments |

Note: The Kruskal-Wallis test showed a significant difference in the level of weed death between treatments in weeks 1 and 2 ($p < 0.05$), while in week 3 there was no significant difference ($p > 0.05$).

Table 6. Results of the Mann-Whitney test on the weed mortality variable between treatments

| Sunday | Treatment Comparison | Mean Rank | *p*-value |
|---|---|---|---|
| Week 1 (MSA) | A vs. B | 5.50[a] vs 15.50[b] | 0.00 |
| | A vs. C | 5.50[a] vs 15.50[b] | 0.00 |
| | B vs. C | 15.50[a] vs 5.50[b] | 0.00 |
| Week 2 (MSA) | A vs. B | 5.50[a] vs 15.50[b] | 0.00 |
| | A vs. C | 5.50[a] vs 15.50[b] | 0.00 |
| | B vs. C | 10.50[b] vs 10.50[b] | 1.00 |

Note: Different letters in the Mean Rank indicate significant difference ($p < 0.05$), and the same letters indicate no significant difference ($p \geq 0.05$)

treatment A still showed the lowest effectiveness and was significantly different from the other two treatments, the effectiveness between manual treatment (B) and paraquat + metsulfuron (C) was no longer significantly different ($p > 0.05$), indicating that the two treatments had equivalent weed control capabilities over time. Thus, it can be concluded that manual control provided the fastest results at the beginning of application, while the paraquat + metsulfuron mixture was able to match the effectiveness of manual control in the following week, while glyphosate + metsulfuron remained the treatment with the lowest effectiveness throughout the observation period.

The difference in effectiveness in mortality rates between treatments is closely related to the different working mechanisms of each weed control method. Manual treatment (B) works physically, namely by cutting the weed directly down to the ground, thereby inhibiting vegetative growth and eliminating competition with the main crop in a short time. According to Hakim *et al*. (2020) Manual weed control can provide effective results in a short time because it directly removes photosynthetically active weed biomass, although its long-term effectiveness is limited by the weed's ability to regenerate from roots or seeds left in the soil. Meanwhile, chemical treatment using paraquat + metsulfuron (C) showed increased effectiveness in the second week because the combination of the two active ingredients works through a rapid and systemic physiological mechanism.

Paraquat is a contact herbicide that inhibits photosynthesis by producing free radicals in chloroplasts, thereby causing rapid tissue necrosis (Leal *et al*., 2023). Whereas metsulfuron methyl is a systemic herbicide of the sulfonylurea group which inhibits enzymes Acetolactate Synthase (ALS), which plays a vital role in the synthesis of essential amino acids such as valine, leucine, and isoleucine. The combination of the two produces a synergistic effect—paraquat provides a rapid effect on green tissue, while metsulfuron provides continued control of broadleaf weeds and more tolerant grasses.

In contrast, treatment A (glyphosate + metsulfuron methyl) showed the lowest effectiveness during the observation period due to glyphosate's slower-acting nature. Glyphosate is a systemic herbicide that inhibits the enzyme 5-enolpyruvylshikimate-3-phosphate synthase (EPSPS), thereby disrupting the shikimate pathway and reducing the production of aromatic amino acids such as tryptophan, tyrosine, and phenylalanine (Duke, 2020). Because glyphosate's action requires translocation and time to induce tissue death, its effects were not yet maximal in the initial observation phase. This is in line with the findings (Kanatas *et al*., 2021) which reported that systemic herbicides such as glyphosate showed optimal effectiveness after 14–21 days of application, especially on weeds with deep root systems. Thus, the results of this study confirm that the variation in response between treatments is caused by differences in the working mechanisms of each weed control agent, both physical and chemical.

### 3.3. Weed Regrowth Rate

Figure 3 shows a decreasing trend in weed regrowth across all treatments as the weeks after application increased. Treatment B maintained a relatively stable and high value, indicating that manual weeding was less effective in suppressing weed regrowth during this observation period. In contrast, treatments A and C showed a consistent decrease, with treatment A showing the sharpest decrease up to 8 WSA, making it the most effective treatment in suppressing weed regrowth. This trend confirms that the effectiveness of weed regrowth suppression differed between treatments, with herbicides performing better than manual methods.

The results of the Kruskal–Wallis test in Table 7 show that in the 6th, 7th, and 8th weeks, the p-value was 0.00 (<0.05) with a significantly different description, meaning that weed regrowth differed significantly among the three treatments. This indicates that the type of control given (glyphosate + metsulfuron methyl, manual, and paraquat + metsulfuron methyl) had different effects on the ability of weeds to regrow after herbicide application and weeding. Thus, it can be concluded that the three control methods have different effectiveness in suppressing weed regrowth during the observation period of weeks 6 to 8.

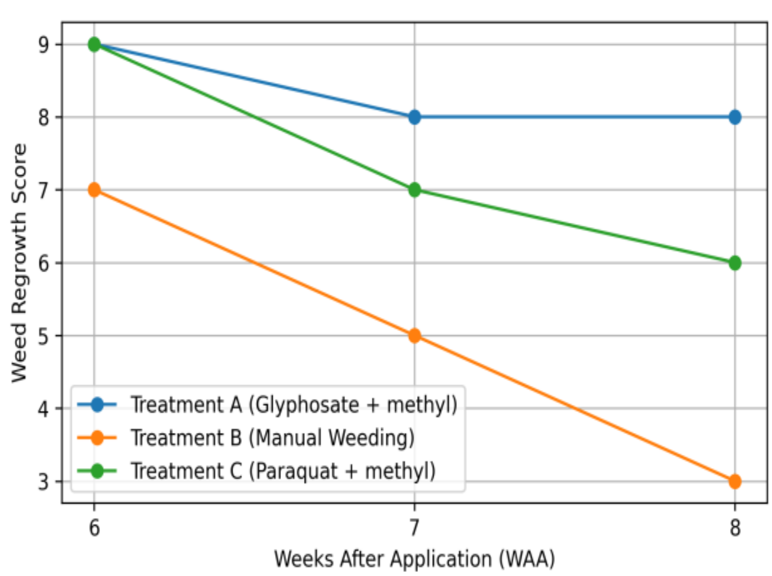


Figure 3. Trend of weed regrowth from week 6 to 8 WAA

Table 7. Results of the Kruskal Wallis test on weed regrowth rate

| Observation Week | H Statistical Value (Chi-Square) | df | *p*-value (Asymp. Sig.) | Mark |
|---|---|---|---|---|
| 6 MSA | 29.00 | 2 | 0.00 | Significant difference |
| 7 MSA | 29.00 | 2 | 0.00 | Significant difference |
| 8 MSA | 29.00 | 2 | 0.00 | Significant difference |

Note: A *p*-value (Asymp. Sig.) < 0.05 indicates that there is a significant difference between treatments, while a p-value ≥ 0.05 indicates no significant difference.

The results of the Mann–Whitney further test in Table 8 show that in weeks 6 to 8, the glyphosate + metsulfuron methyl treatment (A) consistently had the highest mean rank value and was significantly different compared to other treatments, indicating better effectiveness in suppressing weed regrowth. In contrast, the manual treatment (B) and paraquat + metsulfuron methyl (C) tended to have lower mean rank values, resulting in faster recovery of weed growth. This indicates that the glyphosate + metsulfuron methyl mixture was able to provide a longer and more stable control effect on weed regrowth compared to other treatments in the observation period from weeks 6 to 8.

Table 8. Results of the Mann-Whitney test on the variable of weed regrowth between treatments

| Sunday | Treatment Comparison | Mean Rank | *p*-value |
|---|---|---|---|
| 6 WAA | A vs. B | 15.50$^{a}$ vs 5.50$^{b}$ | 0.00 |
| | A vs. C | 10.50$^{b}$ vs 10.50$^{b}$ | 1.00 |
| | B vs. C | 5.50$^{a}$ vs 15.50$^{b}$ | 0.00 |
| 7 WAA | A vs. B | 15.50$^{a}$ vs 5.50$^{b}$ | 0.00 |
| | A vs. C | 15.50$^{a}$ vs 5.50$^{b}$ | 0.00 |
| | B vs. C | 5.50$^{a}$ vs 15.50$^{b}$ | 0.00 |
| 8 WAA | A vs. B | 15.50$^{a}$ vs 5.50$^{b}$ | 0.00 |
| | A vs. C | 15.50$^{a}$ vs 5.50$^{b}$ | 0.00 |
| | B vs. C | 5.50$^{a}$ vs 15.50$^{b}$ | 0.00 |

Note: Different superscript letters indicate significant differences (p < 0.05). The higher the Mean Rank value, the more effective the treatment is in suppressing weed growth. The higher the mean rank, the stronger it is in suppressing weed growth.

The results of the observations show that the dominant weeds, such as *Paspalum conjugatum* and *Asystasia gangetica* respond differently to the control treatments applied. This reflects the physiological and morphological variations between species in response to herbicide stress and mechanical disturbances. *Paspalum conjugatum*, which has the ability to regenerate quickly through stolons and shallow roots, shows a tendency to grow back faster in manual and paraquat + metsulfuron treatments, indicating a high level of tolerance to contact and physical treatments (Baidhawi, 2023) On the contrary,Asystasia gangetica which has thicker stem tissue and high photosynthetic capacity, responded more effectively to the combination of glyphosate + metsulfuron, where this treatment was able to suppress regrowth until the 8th week of observation. This finding is in line with the report (Seng *et al*., 2024) which identifies A. gangeticaas a potentially resistant species to several herbicides in Southeast Asian oil palm plantations, as well as research (Bayyinah *et al*., 2024) which confirms that differences in the mechanisms of action of active ingredients affect the selectivity and resistance of weeds to chemical control. Therefore, the effectiveness of weed control is largely determined by the compatibility between the herbicide's active ingredient and the biological characteristics of the dominant weeds in the field. Therefore, a rotation strategy or combination of chemical and manual methods is necessary to prevent resistance and maintain long-term control effectiveness.

### 3.4. Phytotoxicity

Each treatment given did not show any symptoms of poisoning in the main oil palm plants, so that the treatment using glyphosate + methyl metsulfuron, manual, and paraquat + methyl metsulfuron with the doses used in this study is safe for widespread application, especially in the immature plant phase in oil palm plants. This is shown in Table 9, where the treatments given were observed up to eight weeks after application, and the results of the analysis using the Kruskal Wallis test showed that there were no symptoms of poisoning in the main plants from the first day of observation to the eighth week of observation.

Table 9. Results of the Kruskal Wallis Test on the Phytotoxicity Level of Treatments on Main Plants

| Observation Week | H Statistical Value (Chi-Square) | df | *p*-value (Asymp. Sig.) | Information |
|---|---|---|---|---|
| Week 1 (1 WAA) | 0 | 2 | 1.00 | Not significantly different |
| Week 2 (2 WAA) | 0 | 2 | 1.00 | Not significantly different |
| Week 3 (3 WAA) | 0 | 2 | 1.00 | Not significantly different |
| Week 4 (4 WAA) | 0 | 2 | 1.00 | Not significantly different |
| Week 5 (5 WAA) | 0 | 2 | 1.00 | Not significantly different |
| Week 6 (6 WAA) | 0 | 2 | 1.00 | Not significantly different |
| Week 7 (7 WAA) | 0 | 2 | 1.00 | Not significantly different |
| Week 8 (8 WAA) | 0 | 2 | 1.00 | Not significantly different |

Note: each treatment has a p-value > 0.05 or < 0.05 so there is no real difference between each treatment.

Although the use of herbicides in this study was proven safe for oil palm plants in the immature phase, it is necessary to be aware that repeated application of the same active ingredient can trigger weed resistance (Nugraha & Guntoro, 2022) and have a negative impact on the soil microorganism population (Sakiah, 2023) However, when herbicides are applied at the correct dosage, with rotation of active ingredients, and proper management, these side effects can be minimized and weed control can remain effective and sustainable (Girsang *et al*., 2022).

### 3.5. Cost Evaluation

Table 10 summarizes all components (equipment, materials. And labor) required for weed control activities in oil palm plantations, both manually and chemically. The data presented is secondary data sourced from archives and standard operating procedures (SOPs) at the Johan Sentosa Plantation, thus reflecting actual practices implemented in the field during the immature plant (TBM) management. Each component in the table includes details of the type of work, units, quantity, unit cost, and cost calculations, which illustrate the efficiency of labor and material inputs for each method. In the following table, the total costs for each treatment are summarized to compare the annual cost for weed control using the three options. These calculations will then serve as the basis for cost evaluation and analysis, which can be used as considerations in preparing the annual budget for weed control activities on oil palm discs, especially in the immature plants.

Table 10. Cost component for weed controlling in TBM plants (manual and chemical) in Johan Sentosa Plantation

| Weed Controlling Method | Cost Component | Unit | Quantity | Unit Price (IDR/unit) | Application Cost (IDR/ha) | Annual Cost (IDR/ha) |
|---|---|---|---|---|---|---|
| Manual *) | Labor (man-day) | md †) | 2 | 194,230.00 | 291,345.00 | 582,690.00 |
| | Machete | pcs | | 110,000.00 | 254.63 | 5,970.00 |
| | Whetstone | | | 40,500.00 | 93.75 | 210.00 |
| | APD (Manual) | | | 145,000.00 | 1,438.49 | 751.45 |
| Chemical *) | Labor (man-day) | md †) | 4 | 194,230.00 | 67,980.50 | 271,922.00 |
| | Glyphosate | L | 0.45 | 31,570.00 | 14,206.50 | 56,826.00 |
| | Paraquat | L | 0.45 | 27,143.00 | 12,214.35 | 48,857.40 |
| | Methyl Methsufuronate | kg | 0.0227 | 84,700.00 | 1,922.69 | 7,690.76 |
| | Milk | can | | 12,000.00 | 4,200.00 | 16,800.00 |
| | Knapsack | | | 1,152,000.00 | 11,428.57 | 1,399.00 |
| | Labor | | | 40,000.00 | 396.83 | 48.56 |
| | APD (Sprayer) | | | 305,000.00 | 3,025.79 | 370.29 |

Note: *) Rotation per year is twice (2X) for manual method and 4X for chemical method. †) md = man-day. Standard working capacity for human labor is 1.5 md/ha for manual method, and 0.35 md/ha for chemical method. Work output is 0.67 ha for manual method, and 2.86 ha for chemical method. Labor wage is 194,230.00 IDR/md for both cases.

Table 11. Comparison of annual costs for weed control in the TBM phase of oil palm plantation

| Treatment | Annual cost (IDR/ha) |
|---|---|
| Treatment M1 (Glyphosate + metsufuron-methyl) | 355,056.61 |
| Treatment M2 (Manual) | 589,621.45 |
| Treatment M3 (Paraquat + metsufuron-methyl) | 339,397.25 |

Table 11 shows the annual cost for each weed control treatment per hectare, namely treatment A (glyphosate + metsulfuron-methyl) at 355,056.61 IDR/ha, treatment B (manual) at 589,621.45 IDR/ha, and treatment C (paraquat + metsulfuron-methyl) at 339,397.25 IDR/ha. It can be interpreted that the manual method (treatment B) incurs the highest cost burden compared to the chemical method (treatments A and C). These results are consistent with findings in the literature showing that efficient use of herbicides can reduce labor and time costs compared to manual control (Yu & Marble, 2022). In addition, research on oil palm plants shows that the combination of herbicides such as glyphosate with metsulfuron-methyl increases the effectiveness of weed control, thereby reducing the frequency of applications and operational costs (Rambe *et al*., 2025). However, the use of herbicides must still be balanced with environmental considerations such as nutrient leaching and the risk of weed resistance (Formaglio *et al*., 2020). Thus, the lower costs of this chemical method indicate that for oil palm plantations in the immature phase, choosing a more economical method can be the right strategy to support operational efficiency, while still paying attention to sustainable aspects to support the implementation Good Agricultural Practices in the scope of oil palm plantations.

## 4. CONCLUSION

The results of the study showed that the combination of glyphosate and metsulfuron methyl herbicides was the most effective and cost-efficient weed control method compared to manual weeding and the combination of paraquat and metsulfuron methyl in oil palm discs in the Immature Plant (TBM) phase. This treatment was able to suppress the regrowth of dominant weeds such as *Paspalum conjugatum* and *Asystasia gangetica* up to 8 WAA, with a relatively low annual operational cost of 355,056.61 IDR/ha, compared to the manual method of 589,621.45 IDR/ha. These findings confirm that the use of systemic herbicides glyphosate + metsulfuron methyl provides a balance between control effectiveness, safety for the main crop, and cost efficiency, so it can be used as a practical recommendation in oil palm plantation maintenance activities in the TBM phase.

However, this study is limited by its relatively short observation timescale (eight weeks) and the testing of only two herbicide combinations, so the results do not fully reflect the long-term dynamics of weed populations. Therefore, further research is needed with long-term field trials to assess the consistency of effectiveness, potential environmental impacts, and effects on soil biota. Further studies are also recommended to explore variations in dosage, application intervals, and the integration of manual and chemical methods within an integrated weed management framework to increase cost efficiency while supporting the sustainability of oil palm plantation management.


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## AUTHOR CONTRIBUTION STATEMENT

| Author | C | M | So | Va | Fo | I | R | D | O | E | Vi | Su | P | Fu |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| HWH | ✓ | ✓ | | | | ✓ | | ✓ | ✓ | ✓ | | | | |
| Har | | ✓ | | ✓ | ✓ | | ✓ | | | ✓ | | ✓ | ✓ | |

C: Conceptualization; M: Methodology; So: Software; Va: Validation; Fo: Formal Analysis; I: Investigation; D: Data Curation; R: Resources; O: Writing - Original Draft; E: Writing - Review & Editing; Vi: Visualization; Su: Supervision; Fu: Funding Acquisition; P: Project Administration

## REFERENCES


Ahmal, V.J., Ilmiasari, Y., Harini, N.V.A., & Novrimansyah, E.A. (2025). Efektivitas herbisida bahan aktif Haloxyfop-R Methyl Ester terhadap gulma belulang (*Eleusine indica* L.). *Journal of Agriculture and Animal Science, **5***(2), 212–220.

Arbania, I.O., Sudirman, A., Sari, S., & Syofian, M. (2021). Efikasi kombinasi herbisida metil metsulfuron dan asam asetat pada lahan perkebunan kelapa sawit (*Elaeis guineensis* Jacq.). *Jurnal Agro Industri Perkebunan*, ***9***(1), 23–34. https://doi.org/10.25181/jaip.v9i1.1425

Baidhawi, B. (2023). The effectiveness of mixing herbicides and manual weed control on corn (*Zea mays* L.). *Jurnal Agrium, **20***(2), 185–193. https://doi.org/10.29103/agrium.v20i2.12509

Bayyinah, L.N., Purwanto, P., Syarifah, R.N.K., & Pratama, R.A. (2024). Respons fisiologis tanaman jagung manis terhadap aplikasi herbisida dalam pengendalian gulma. *Jurnal Agro Wiralodra*, *7*(2), 66–74.

Bilkis, F.G., Chozin, M.A., & Guntoro, D. (2022). Pergeseran dominasi gulma kebun kelapa sawit IPB Jonggol dan kemungkinan resistensi terhadap herbisida glifosat. *Indonesian Journal of Agronomy, **50***(1), 115–122.

Bin Che Ruzlan, K.A., Ahmad, M.S., & Hamdani, A. (2021). Integrated weed management programs at oil palm plantation — A survey. *International Journal of Agriculture, Forestry and Plantation, **11***, 32–38.

Direktorat Pupuk dan Pestisida, Direktorat Jenderal Prasarana dan Sarana Pertanian, Kementerian Pertanian Republik Indonesia. (2012). *Metode standar pengujian efikasi pestisida T.A. 2012*. Jakarta: Kementerian Pertanian Republik Indonesia.

Duke, S.O. (2020). Integrated weed management programs at oil palm plantation — A survey. *Weed Science, **68***(3), 201–207. https://doi.org/10.1017/wsc.2019.28

EWRC (European Weed Research Council). (1964). Report of the 3rd and 4th meetings of the European Weed Research Council, Committee of Methods in Weed Research. *Weed Research, **4***(1), 88.

Formaglio, G., Veldkamp, E., Duan, X., Tjoa, A., & Corre, M.D. (2020). Herbicide weed control increases nutrient leaching compared to mechanical weeding in a large-scale oil palm plantation. *Biogeosciences, **17***(21), 5243–5262. https://doi.org/10.5194/bg-17-5243-2020

GAPKI (Gabungan Pengusaha Kelapa Sawit Indonesia). (2025). *Press release: CPO and PKO production and consumption in 2024 experiences a slight decline*. Jakarta: GAPKI.

Girsang, W., Meriaty, Z.R., Rahadian, Z., Girsang, R., & Purba, W. (2022). Efektifitas herbisida glifosat dengan penambahan surfaktan untuk mengendalikan gulma di lahan kelapa sawit (Elaeis quineensis Jacq). *Jurnal Agrotek Indonesia, **7***(2), 5–12. https://journal.unsika.ac.id/index.php/agrotek/article/view/6908

Hakim, D.B., Hadianto, A., Giyanto, Hutaria, T., & Amaliah, S. (2020). The production efficiency of herbicides in palm oil plantation in Sumatera and Kalimantan. *IOP Conference Series: Earth and Environmental Science*, ***468***(1), 012054. https://doi.org/10.1088/1755-1315/468/1/012054

Haryanti, N., & Marsono, A. (2021). Strategi implementasi pengembangan perkebunan kelapa sawit di era industri 4.0. *Jurnal Dinamika Ekonomi Syariah, **8***(1), 76–87. https://doi.org/10.53429/jdes.v8i1.146

Kanatas, P., Antonopoulos, N., Gazoulis, I., & Travlos, I.S. (2021). Screening glyphosate-alternative weed control options in important perennial crops. *Weed Science, **69***(6), 704–718. https://doi.org/10.1017/wsc.2021.55

Kaur, A., Singh, G., Menon, S., & Kumari, K. (2024). Integrated weed management: A comprehensive review of conventional, non-conventional, and emerging strategies for sustainable agriculture. *Journal of Advances in Biology & Biotechnology, **27***(8), 156–167. https://doi.org/10.9734/jabb/2024/v27i81130

Leal, J.F.L., Borella, J., dos Santos Souza, A., Langaro, A.C., de Moura Carneiro, R., de Souza da Silva, G., de Oliveira Junior, F.F., Ramos de Souza, F., Machado, A.F.L., & De Pinho, C.F. (2023). Photosystem II- and photosystem I-inhibitor herbicides-driven changes in the dynamics of photosynthetic energy dissipation of *Conyza* spp. *Acta Physiologiae Plantarum, **45***(8), 94. https://doi.org/10.1007/s11738-023-03572-1

Al Ansori, M., Mahmud, Y., & Elfianis, R. (2025). Uji efektivitas herbisida isopropilamina glifosat dan metil metsulfuron dalam mengendalikan gulma di perkebunan kelapa (*Cocos nucifera* L.). *Prosiding Seminar Nasional Integrasi Pertanian dan Peternakan*, ***3***(1), 39–49. https://semnasfpp.uin-suska.ac.id/index.php/snipp/article/view/121

Kementerian Pertanian Republik Indonesia. (2024). *Outlook komoditas perkebunan kelapa sawit tahun 2024* (Pusat Data dan Sistem Informasi Pertanian, Sekretariat Jenderal). Jakarta: Kementerian Pertanian RI. https://satudata.pertanian.go.id/details/publikasi/696

Nugraha, K., & Guntoro, D. (2022). Dominansi dan potensi resistensi gulma *Eleusine indica* terhadap herbisida glifosat di Kebun Pendidikan Kelapa Sawit Jonggol, Jawa Barat. *Buletin Agrohorti,* ***10***(3), 340–348. https://doi.org/10.29244/agrob.v10i3.46451

Nduru, E.N.I., Lizmah, S.F., Subandar, I., Chairuddin, C., & Arisyi, M.A. (2023). Analisis vegetasi gulma pada perkebunan kelapa sawit (*Elaeis guineensis* Jacq.) di Area Afdeling I, Kebun Jaya Seujahtera, PT. ASN. *Biofarm : Jurnal Ilmiah Pertanian,* ***19***(1), 7–16. https://doi.org/10.31941/biofarm.v19i1.2529

Rambe, S.P., Gunawan, T.R., Priwiratama, H., & Prasetyo, A.E. (2025). Effectiveness of glyphosate and metsulfuron-methyl herbicide mixtures for weed management in oil palm plantations. *IOP Conference Series: Earth and Environmental Science,* ***1494***(1), 012008.

Ramlan, D.N., Riry, J., & Tanasale, V.L. (2019). Inventarisasi jenis gulma di areal perkebunan karet (*Hevea brasiliensis*) pada ketinggian tempat yang berbeda di Negeri Liang, Kecamatan Teluk Elpaputih, Kabupaten Maluku Tengah. *Jurnal Budidaya Pertanian,* ***15***(2), 80–91. https://doi.org/10.30598/jbdp.2019.15.2.80

Sakiah, S., Guntoro, G., & Manullang, A.M. (2021). Pengaruh herbisida berbahan aktif paraquat terhadap persentase kematian gulma dan jumlah mikroorganisme tanah. *Jurnal Agro Estate*, ***4***(2), 99–108. https://doi.org/10.47199/jae.v4i2.73

Sari, R.P.K., & Pujisiswanto, H. (2024). Efikasi herbisida parakuat diklorida terhadap gulma di perkebunan kopi tanaman belum menghasilkan. *Gontor Agrotech Science Journal,* ***10***(2), 101–109.

Seda, F. (2022). Pengaruh herbisida campuran paraquat dan metil metsulfuron untuk mengendalikan gulma Dicranopteris linearis di kebun kelapa sawit. [*Undergraduate Thesis*], Institut Pertanian Yogyakarta. https://eprints.instiperjogja.ac.id/id/eprint/4335

Seng, C.T., Yusop, N., Pauzi, S.A., Ramli, N.K.C.M., Aani, S.N.A., Sahal, M.S.A.M., Pahang, J.T., Purba, E., & Sa'adah, N. (2024). Survey of herbicide-resistant weed management in oil palm estates from Peninsular Malaysia and Indonesia. *Advances in Weed Science, **42***, e020240030. https://doi.org/10.51694/AdvWeedSci/2024;42/00020

Silva, R., Sobral, A.F., Dinis-Oliveira, R.J., & Barbosa, D.J. (2024). The link between paraquat and demyelination: A review of current evidence. *Antioxidants,* ***13***(11), 1354. https://doi.org/10.3390/antiox13111354

Singh, S., Kumar, V., Gill, J.P.K., Datta, S., Singh, S., Dhaka, V., Kapoor, D., Wani, A.B., Dhanjal, D.S., Kumar, M., Harikumar, S.L., & Singh, J. (2020). Herbicide glyphosate: Toxicity and microbial degradation. *International Journal of Environmental Research and Public Health,* ***17***(20), 7519. https://doi.org/10.3390/ijerph17207519

Situmorang, R., Mawandha, H.G., & Suryanti, S. (2023). Efektifitas dan efisiensi pengendalian secara manual (Si Jari Tiga) dan kimia (metil metsulfuron) terhadap gulma *Asplenium* sp. di kebun kelapa sawit. *AGROFORETECH,* ***1***(3), 1628–1632. https://jurnal.instiperjogja.ac.id/index.php/JOM/article/view/920

Tang, W., Liu, S., Yu, X., Yang, Y., Zhou, X., & Lu, Y. (2021). The basis of tolerance mechanism to metsulfuron-methyl in *Roegneria kamoji* (Triticeae: Poaceae). *Plants,* ***10***(9), 1823. https://doi.org/10.3390/plants10091823

Yu, P., & Marble, S.C. (2022). Practice in nursery weed control—Review and meta-analysis. *Frontiers in Plant Science,* ***12***, 807736. https://doi.org/10.3389/fpls.2021.807736