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RESEARCH ARTICLE OPEN ACCESS

Resistance of Eleusine Indica (L.) Gaertn to Paraquat and Glyphosate in Oil Palm Plantations and Evaluation of Propaquizafop as an Alternative Control

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Abstract:

Introduction: *Eleusine indica* (L.) Gaertn. is a common grass weed frequently found in oil palm plantations. In the West Kalimantan and Riau Provinces of Indonesia, oil palm growers are increasingly reporting reduced herbicide efficacy, raising concerns about the long-term sustainability of current weed management practices. This study aimed to (1) confirm the levels of resistance to glyphosate and paraquat in *E. indica* and (2) evaluate the effectiveness of the herbicide propaquizafop in controlling resistant populations.

Methods: Seeds of *E. indica* suspected to be herbicide-resistant were collected from oil palm fields in West Kalimantan and Riau, while seeds of the susceptible biotype were obtained from West Java. Resistance testing was conducted using the whole-plant pot assay method. Glyphosate, paraquat, and propaquizafop were applied at seven dose levels: 0, 0.25, 0.5, 1, 2, 4, and 8 times the recommended field rate.

Results: Eleusine indica populations from Riau and West Kalimantan were confirmed to be multiple herbicide resistant to both glyphosate and paraquat. The resistance index values were 2.58 and 4.36 for glyphosate and 2.30 and 3.37 for paraquat, respectively. However, the resistant biotypes remained susceptible to propaquizafop, with resistance index values of less than 2.

Discussion: These findings are consistent with previous reports indicating that *E. indica* in Malaysia has developed multiple resistance to fluazifop-P-butyl, paraquat, glufosinate, and glyphosate [23]. However, further research is needed to identify effective herbicide mixtures and alternative herbicides with different modes of action for managing resistant populations. Additionally, a comprehensive investigation of the underlying resistance mechanisms is essential to inform sustainable weed management strategies.

Conclusion: The findings of this study suggest that propaquizafop is a promising alternative herbicide for managing *Eleusine indica* populations resistant to paraquat and glyphosate.

Keywords : Competition , *Elaeis guineensis* , Herbicides , Weed , *Eleusine indica*, Palm oil .

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1. INTRODUCTION

The provinces of West Kalimantan and Riau are among the largest oil palm-producing areas in Indonesia. West Kalimantan covers an area of 1.829.533 hectares, with a production of 5,332, 338 tonnes in 2023. Riau province covers an area of 3.494.583 hectares, with a production of 8.961.940 tons in 2023 [1]. Presently, Indonesia stands as the foremost palm oil producer on a global scale, boasting a plantation area that encompasses 14.17 million hectares [2]. In Indonesian oil palm farms, herbicide application for weed management is more prevalent than alternative methods. Weed control using herbicides is more practical and profitable, as it requires less time and labour [3]. It has been reported to be up to 80% more profitable than traditional weeding methods [4].

Weed is a major factor affecting oil palm plantations by reducing the quality and quantity of production due to competition for nutrients, 40% of the damage to crops, both in terms of quality and quantity, was attributable to diverse types of weeds, diseases, insects, and animals [5]. Weed has a greater economic impact on production than insects, fungi, or other plant pests [6]. The presence of *Eleusine indica* weed causes losses to oil palm cultivation in both producing mature plants, immature plants, and main nursery areas [7]. Weed infestations in oil palm plantations may reduce production by 25-40% [8]. A typical example of a weed frequently predominant in oil palm farms is *E. indica*.

The emergence of herbicide-resistant weeds significantly reduces the number of effective herbicide options, leading to increased failure rates in weed control efforts [9]. Furthermore, resistant weed renders herbicide applications ineffective, prompting farmers to adopt alternative control methods that may be more expensive. This situation affects both production costs and the effectiveness of weed control [10].

Resistance to herbicides occurs due to a lack of herbicide rotation and continuous application over a long period [3]. A previous study defined weed resistance to herbicides as the ability to survive after the administration of herbicide, even at higher doses. The persistent use of herbicides with the same active ingredient or mechanism of action can lead to a substantial rise in the population of resistant weeds that endure. This condition may result in larger populations of resistant weeds, making herbicide control ineffective [9].

Cases of weed resistance have increased globally each year, reducing the number of effective herbicide options available [11]. In 2017, there were 494 resistant weed biotypes, experiencing an increase in 2024 to 531. Presently, there are 27 documented instances of *E. indica* exhibiting resistance to several herbicides worldwide, including resistance to propaquizafop (1 case), paraquat (1 case), and glyphosate (16 cases). An example of this case is *E. indica* resistance to glyphosate in the oil palm fields of Serdang Begadai, North Sumatra province, Indonesia [12]. The rotation of herbicide types with different modes of action represents a potential strategy for the management of resistant weeds [13].

The rationale for this study is based on the limited availability of information on resistant weeds in Indonesia. However, there is a substantial body of knowledge from local farmers showing that effective herbicides have become ineffective against some weed species, including *E. indica.* This lack of information is attributable to the limited study conducted and the low level of knowledge among farmers regarding weed resistance. The framework of this study is to confirm the resistant nature of *E. indica* weed from West Kalimantan and Riau to various herbicides, thereby elucidating the suitability for use in a rotation programme aimed at controlling the resistant weed.

2. MATERIALS AND METHODS

2.1. Plant Material

The materials used in this study included *E. indica* weed from Karang Pamulang Village, Mandalajati Subdistrict, Bandung City, West Java, 6°53'52.0"S 107° 40'21.0" E as control (*E. indica* susceptible/ES), Ukui Dua Village, Ukui Subdistrict, Indragiri Hulu Regency, Riau, 0°09'02.8"S 102°13'23.8" E (*E. indica* resistance 1/ER1), and Laman Satong Village, North Matan Hilir subdistrict, Ketapang District, West Kalimantan, 1°21'40.5"S 110°09'12.1"E (*E. indica* resistance 2/ER2).

2.2. Experimental Design

The experimental design employed was a split-plot design comprising two components with three replications. The primary factor comprises seven levels as the main plot: 0, 0.25, 0.5, 1, 2, 4, and 8 times the recommended dosage for each herbicide (400 g a.i. ha^{-1} for paraquat (Gramoxone 256 SL, PT. Syngenta, Indonesia), 750 g a.i. ha^{-1} for glyphosate (Roundup 486 SL, PT. Monagro Kimia, Indonesia), and 100 g a.i. ha^{-1} for propaquizafop (Agil 100 EC, PT. Royal Agro, Indonesia)). The second factor was *E. indica* weed biotypes consisting of three biotypes as subplots. *E. indica* was planted in 18 cm diameter pots containing sterilised soil media with ± 30 seeds/pot. Thinning and replanting were carried out for 25 days, and then the *E. indica* was weeded to leave 10 samples per pot. Herbicide was applied four weeks post-planting, utilizing a semi-automatic backpack sprayer equipped with flat fan nozzles at a pressure of 1 kg/cm (15-20 p.s.i). The amount of water used was 400 l/ha, and spraying was carried out according to the tested dosage.

2.3. Measurements of Morphological Parameters

In each experimental unit, weed dry weights were determined by destruction. Weed was harvested 4 weeks after application. Samples of *E. indica* that remained alive in each treatment were severed at the stem's base and subsequently subjected to an oven at 80 °C for 48 hours to achieve a consistent dry weight [13]. The data of the dry weight were converted into a percentage of growth reduction by making a comparison between *E. indica* treated with herbicide (T) and *E. indica* without herbicide application (C) in each region of origin. The formula used in this case for percentage conversion is (Eq. **1**) [13]

$$\text{Growth Reduction (\%)} = (1-(T/C)) \times 100\% - (1) \qquad (1)$$

2.4. Statistical Analysis

Data were analyzed with ANOVA (analysis of variance), and in instances of significant differences, the Scott-Knott post hoc test was performed at the 5% level using IBM SPSS Statistics 20 software. Non-linear regression analysis of the log-logistic model was used to obtain the GR_{50} value. The analysis was performed using Origin Pro software version 2016 [14]. GR_{50}, or growth reduction analysis, denotes the herbicide dosage necessary to attain a 50% decrease in weed growth. The obtained GR_{50} data were used to determine the resistance ratio of the weed. Resistance ratio (NR) is the value obtained by comparing the GR_{50} of resistant *E. indica* with the GR_{50} of susceptible *E. indica*. Resistance classification is based on NR value with the criteria NR < 2, NR 2-6, NR > 6-12, and NR > 12 as susceptible, low resistant, moderately resistant, and highly resistant [15].

3. RESULT

3.1. Growth Reduction of *Eleusine Indica* Weed to Various Herbicide

The effects of glyphosate on growth reduction in *E. indica* are presented in Table **1**. When *E. indica* was treated with glyphosate at 2 to 8 times the recommended dose (1500–6000 g a.i. ha^{-1}), a 100% growth reduction was observed. This indicates that the weeds were completely controlled at these treatment levels. Glyphosate application reduced growth in ER1 and ER2 populations; however, no complete weed mortality was observed even at the highest dose (6000 g a.i. ha^{-1}). In contrast, the ES population exhibited complete mortality at just twice the recommended dose (1500 g a.i. ha^{-1}).

Table 1. Effects of different herbicide applications on *E. indica* growth reduction (%).

Herbicide	Biotypes	Herbicide						
		0	0.25	0.5	1	2	4	8
Glyphosate	ES	0.00 a,D	43.50 a,C	50.59 a,C	85.19 a,B	100.00 a,A	100.00 a,A	100.00 a.A
	ER1	0.00 a,F	9.84 b,E	37.21 b,D	52.78 b,C	66.52 b,B	88.34 a,A	97.68 a,A
	ER2	0.00 a,F	13.6 b,E	24.35 c,D	31.33 c,D	55.42 b,C	71.99 b,B	98.73 a,A
Paraquat	ES	0.00 a,D	46.75 a,C	58.21 a,B	97.49 a,A	100.00 a,A	100.00 a,A	100.00 a,A
	ER1	0.00 a,G	33.71 b,F	40.91 b,E	54.48 b,D	69.00 b,C	79.91 b,B	96.36 a,A
	ER2	0.00 a,F	15.87 c,E	27.97 c,D	43.30 c,C	67.79 b,B	100.00 a,A	100.00 a,A
Propaquizafop	ES	0.00 a,D	43.09 b,C	68.20 b,B	100.00 a,A	100.00 a,A	100.00 a,A	100.00 a,A
	ER1	0.00 a,E	37.51 c,D	60.14 c,C	79,76 b,B	100.00 a,A	100.00 a,A	100.00 a,A
	ER2	0.00 a,B	100.00 a,A	100.00 a,A	100.00 a,A	100.00 a,A	100.00 a,A	100.00 a,A

Note: The values in each column denoted by identical lowercase letters (vertically) and uppercase letters (horizontally) are not statistically different at $p < 0.05$, as determined by the Scott-Knott Test for each herbicide.

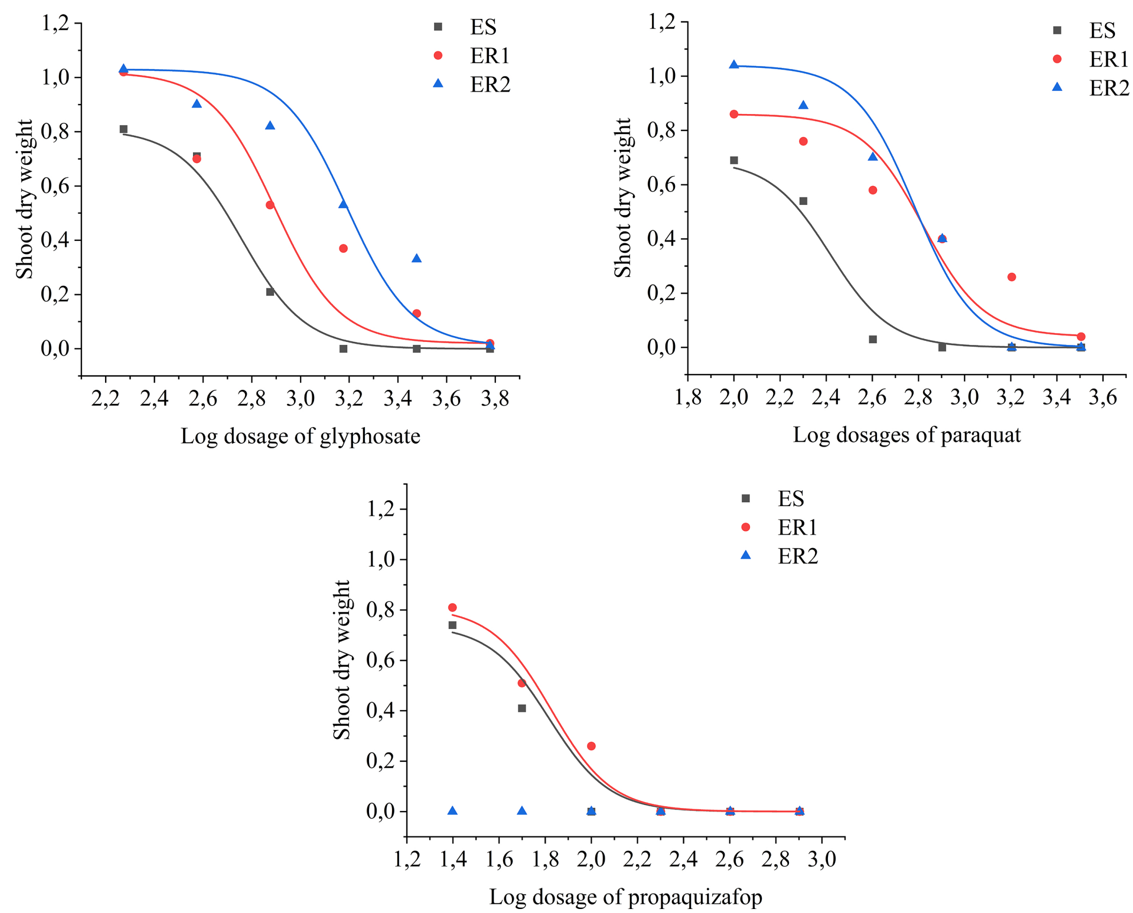

Fig. (1). The growth reduction curves of resistant and susceptible *E. indica* biotypes following the application of herbicide.

Table 2. GR_{50} values of *E. indica* weed against herbicide

Herbicide	Biotype	*p*	r^2	GR_{50}	Resistance Index	Level of Resistance
Glyphosate	ES	1.50	0.92	271.97	-	Susceptible
	ER1	1.28	0.97	702.92	2.58	Low Resistance
	ER2	1.24	0.96	1,187.59	4.36	Low Resistance
Paraquat	ES	1.70	0.91	122.68	-	Susceptible
	ER1	0.85	0.97	283.04	2.30	Low Resistance
	ER2	1.53	0.96	414.25	3.37	Low Resistance
Propaquizafop	ES	2.08	0.96	30.01	-	Susceptible
	ER1	1.58	0.98	36.58	1.21	Susceptible
	ER2	-	-	-	-	Susceptible

The result in Table **1** shows that plants treated with paraquat at doses ranging from 1-8 times the recommended dosage (400 to 3200 g a.i. ha^{-1}) had a 97 to 100% reduction in growth or mortality. However, plants treated with ER1 and following the application of the recommended dose of paraquat, ER2 showed survival, even at the highest dose. The growth reduction value was 96.36% for ER1 and up to twice the recommended dose, with 67.79% for ER2. This result suggested that ER1 and ER2 were not susceptible to the effects of paraquat. Table **1** showed that plants treated with propaquizafop at the recommended dosage (100 g a.i. ha^{-1}) experienced a reduction in growth, with values of 100, 79.76, and 100% observed for ES, ER1, and ER2, respectively. This result showed that ES and ER2 could be effectively controlled by propaquizafop at the recommended dose.

3.2. GR_{50} and Weed Resistance Index of *Eleusine indica*

GR_{50} values for each biotype against glyphosate, paraquat, and propaquizafop were determined using the equation in Fig. (**1**). These values represented the dose required to control each *E. indica* weed biotype with a 50% probability of growth reduction. The analysis showed that GR_{50} values of ER1 and ER2 against glyphosate, 702.92 and 1,187.59, were considerably higher than 271.97 of ES. GR_{50} values of each weed biotype against glyphosate (Table **2**) showed that ER1 and ER2 had low resistance to herbicide. Resistance index values for ER1 and ER2 are 2.58 and 4.36, respectively. Furthermore, the GR_{50} value of *E. indica* against paraquat was 283.04 and 414.25 for ER1 and ER2, respectively. Based on the GR_{50} value of each weed biotype against paraquat, the resistance index value for ER1 was 2.3, and for ER2 was 3.37.

The result in Table **2** shows that ER1 and ER2 fall into the category of weed with low resistance to paraquat. The GR_{50} value of *E. indica* against propaquizafop for ER1 and ER2 was 36.58 and uncalculated, respectively. Furthermore, the GR_{50} value of each weed biotype against propaquizafop shows resistance index values <2. This result signifies that ES, ER1, and ER2 are included in the category of weeds susceptible to propaquizafop herbicide.

4. DISCUSSION

The application of paraquat and glyphosate was generally effective in controlling the growth of *E. indica* weed. Glyphosate inhibits the enzyme 5- enolpyruvyl shikimate -3-phosphate synthase (EPSPS), integral to the shikimate pathway in plants. This route is required for the biosynthesis of aromatic amino acids, such as tryptophan, tyrosine, and phenylalanine, which are vital for plant growth and development [16]. Paraquat inhibits the photosynthetic process, particularly photosystem I, disrupting the reduction of $NADP^+$ to NADPH. This disruption leads to the generation of free radicals, which react with oxygen to form hydrogen peroxide. The accumulation of hydrogen peroxide damages cell membranes and plant tissues, ultimately causing weed death characterized by leaf necrosis and signs of wilting [17, 18].

The mean growth reduction values observed for ER1 and ER2 were found to be lower than ES in herbicide treatments using glyphosate and paraquat. A similar phenomenon was observed in *E. indica* weed from Adolina Plantation PTPN IV Serdang Bedagai, North Sumatra Province. This weed was previously documented to exhibit resistance and showed a lower average growth reduction compared to susceptible biotype *E. indica* weed following exposure to herbicides that inhibit photosystem 1 processes [19]. The reduction in dry weight of *E. indica* weed observed at each treatment dose was attributed to the application of herbicides in conjunction with higher doses and the mechanism of action [20]. The *E. indica* population from oil palm plantations at the Adolina Plantation of PTPN IV Serdang Bedagai was determined to be resistant to glyphosate and paraquat [21].

The study reported that *E. indica* ER1 and ER2 exhibited resistance to glyphosate and paraquat. This result is consistent with a report that showed *E. indica* from China had resistance to glyphosate, paraquat, and glufosinate herbicides [16]. The information regarding this resistance case increases the difficulty of controlling *E. indica* weed in oil palm plantations, as glyphosate and paraquat were the most widely used [22]. In addition, the *E. indica* population in oil palm farms within Batu Bara Regency exhibited a glyphosate resistance rate of 63.33% [12].

The history of herbicide use, dose, frequency, and application method were among the factors that increased resistance in weed [23]. The populations of ER1 and ER2 were gathered from oil palm fields in Riau and West Kalimantan, where the persistent application of glyphosate and paraquat has been a prevalent practice for the last decade. According to farmers in these locations, the application of glyphosate and paraquat existed for the last 10 years with a frequency of 4-6 times annually. This result is consistent with the report that *E. indica* exhibited multiple resistance to fluazifop-P-butyl, paraquat, glufosinate, and glyphosate herbicides in Malaysia [23]. A previous study confirmed that weed was resistant to glyphosate with a moderate category [24]. The present study is substantiated by the documented findings of *E. indica*, which has been identified as exhibiting resistance to paraquat with index values of 5 and 9 in Benjire Village and Perlamben Sub-district, Tigabinaga Karo District [25].

The result of this study showed that both ER1 and ER2 were vulnerable to ACCase enzyme inhibitor herbicide, containing propaquizafop as the principal component. Therefore, ACCase inhibitor is a viable alternative to conventional herbicides for the control of *E. indica*, which has been identified as having multiple resistance to aromatic amino acid and photosystem I inhibitor herbicides. ACCase-inhibiting herbicide has been shown to provide effective weed control against grass-type weeds [26]. This outcome aligns with a report that the use of propaquizafop herbicide can control *E. indica* weed [27]. The result was also consistent with a report that showed that the ACCase inhibitor effectively lowers the dry weight of certain grass weeds [5].

The application of herbicide rotation is important in controlling weeds to minimize the occurrence of resistance in the agricultural sector. According to a previous study, the phenomenon of multiple resistance occurs when a weed is resistant to different types of herbicides and modes of action [28]. Therefore, the control of *E. indica* weed resistant to glyphosate and paraquat can be achieved through the use of propaquizafop as an alternative [13]. Based on the results, farmers are required to have insight and knowledge about herbicide rotation and type selection in order to avoid the development of more complex resistance cases in the future.

CONCLUSION

Eleusine indica biotypes from Riau and West Kalimantan were identified as resistant to glyphosate with resistance index values of 2.58 and 4.36, and to paraquat, with values of 2.30 and 3.37. However, these biotypes were effectively controlled by the herbicide propaquizafop. This study demonstrates that propaquizafop herbicide can be utilized as an alternative herbicide to manage glyphosate and paraquat-resistant *E. indica*. However, further research is needed to identify mixed herbicides and those with different modes of action that can effectively control resistant weeds. A comprehensive evaluation of the underlying resistance mechanisms is also essential to support effective management strategies, including herbicide rotation.

AUTHORS' CONTRIBUTIONS

D.K.: Conceptualization; D.K., R.W., and U.U.: Methodology; R.W., S.S.: Software; D.K.: Validation; D.K.: Formal analysis; D.K., R.W., S.S.: Investigation; D.K.: Resources; D.K., R.W., and S.S.: Data curation; D.K.: Writing-original draft preparation; D.K. and R.W.: Writing-review and editing; D.K. and R.W.: Visualization; D.K.: Project administration; D.K.: Funding acquisition; All authors have read and agreed to the published version of the manuscript.

ABBREVIATION

E. indica = *Eleusine indica*

RESEARCH INVOLVING PLANTS

Not applicable.

CONSENT FOR PUBLICATION

Not applicable.

AVAILABILITY OF DATA AND MATERIALS

The data sets used and/or analysed during this study are available from the corresponding author [D.K] upon request.

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None.

CONFLICT OF INTEREST

The authors declare no conflict of interest financial or otherwise.

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