

## Comparative Efficacy of Florpyrauxifen-Benzyl, 2,4-D, and Penoxsulam on Water Hyacinth (*Eichhornia crassipes* [Mart.] Solms)

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**Abstract.** Water hyacinth (*Eichhornia crassipes* [Mart.] Solms) is one of the most problematic invasive aquatic weeds, causing severe ecological and economic damage in tropical regions. Herbicides are often considered the most efficient approach for managing aquatic weeds compared to mechanical or biological control methods. However, conventional herbicides such as 2,4-dichlorophenoxyacetic acid (2,4-D) require high application rates and may pose environmental risks. Therefore, new herbicides with greater efficacy at lower doses and improved environmental safety are required. This study aimed to evaluate the effectiveness of florpyrauxifen-benzyl, a novel auxin-mimicking herbicide, compared with 2,4-D and penoxsulam in suppressing the growth of *E. crassipes*. The experiment was conducted from April to June 2022 under greenhouse and open-field conditions using a randomized complete block design with ten treatments, each with three replications, namely Florpyrauxifen-benzyl (FB, 10 g a.i./ha), Penoxsulam (P, 12.5 g a.i./ha), and 2,4-D (400 g a.i./ha). The parameters observed included phytotoxicity symptoms, water loss, dry weight, and damage percentage. The results revealed that florpyrauxifen-benzyl at 15–20 g a.i./ha provided growth suppression comparable to 2,4-D at 600 g a.i./ha, while penoxsulam exhibited lower efficacy. In conclusion, florpyrauxifen-benzyl demonstrates strong potential as a low-dose, environmentally safer, and sustainable herbicide for the management of water hyacinth under tropical conditions in Indonesia, offering practical benefits in reducing chemical inputs for aquatic weed control programs.

**Keywords:** *Eichhornia crassipes*, florpyrauxifen-benzyl, herbicide efficacy, penoxsulam, 2,4-dichlorophenoxyacetic acid

## INTRODUCTION

Aquatic weeds are among the most problematic invasive species in tropical regions because they disrupt ecosystems, obstruct waterways, and reduce biodiversity. One of the most aggressive species is water hyacinth (*Eichhornia crassipes* [Mart.] Solms), a free-floating aquatic plant that rapidly proliferates in nutrient-rich environments. Its dense mats block sunlight penetration, reduce dissolved oxygen levels, and accelerate sedimentation, leading to substantial ecological

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and economic losses in many tropical countries, including Indonesia (Lestari et al., 2018; Nandi-yanto et al., 2024). Effective management of *E. crassipes* is therefore crucial for maintaining aquatic ecosystem functions and supporting water-based livelihoods.

Various methods have been applied to control *E. crassipes*, including mechanical removal, biological agents, and integrated management. However, herbicides remain the most practical and effective approach due to their rapid action, scalability, and lower labor requirements (Gettys et al., 2014; Zimdahl, 2018; Zhou et al., 2023). Among these, 2,4-dichlorophenoxyacetic acid (2,4-D), a synthetic auxin commonly used as a herbicide, was selected as a benchmark because it has been widely applied and proven effective for aquatic weed control, providing a well-established standard for comparison (Park et al., 2017). Penoxsulam, an acetolactate synthase (ALS) inhibitor, was included as an alternative mode of action to assess FPB performance under a different mechanism of action (Park et al., 2017). More recently, florpyrauxifen-benzyl (FPB), a novel synthetic auxin herbicide, has shown strong efficacy against *E. crassipes* at very low doses in several countries (Lee et al., 2014; Mudge et al., 2021), highlighting its potential as an innovative alternative to conventional herbicides.

Despite these advances, few studies have evaluated the performance of FPB under tropical conditions, particularly in Indonesia, where high temperatures, light intensity, and water chemistry may influence the activity of synthetic auxin herbicides. Generally, high temperatures can enhance herbicide uptake and translocation within plant tissues, while light intensity affects photosynthetic activity, which in turn can modulate plant sensitivity to auxins. Water chemistry, such as pH and hardness, may also alter herbicide solubility and availability. These factors collectively contribute to the variability in herbicide efficacy observed in aquatic weed management (Daramola et al., 2022). Comparative studies among FPB, 2,4-D, and penoxsulam are also scarce, leaving uncertainty about dose optimization, relative effectiveness, and environmental implications. A recent field study in Indonesia reported that FPB at 15 g a.i./ha achieved complete control of *E. crassipes* in a tropical lake (Kurniadie et al., 2023). Brown et al. (2022) reported that 2,4-D effectively reduced the biomass and coverage of *E. crassipes* under field conditions, demonstrating its effectiveness as a chemical control agent in aquatic weed management. However, the broader applicability of these findings across diverse aquatic ecosystems remains poorly understood. Furthermore, ecotoxicological and water-quality considerations have not been fully addressed, particularly in sensitive tropical freshwater habitats.

Therefore, this study was conducted to evaluate the effectiveness of FPB in controlling *E. crassipes* under tropical conditions in Indonesia, in comparison with 2,4-D and penoxsulam (Riner et al., 2025). The specific objective was to determine the minimum effective dose of FPB for growth suppression and to assess its potential as a sustainable alternative to conventional herbicides. This research provides new insight into the practical and environmental advantages of FPB-based management for tropical aquatic weed control, contributing to the development of more efficient and eco-friendly weed management strategies in Indonesia.

## MATERIALS AND METHODS

### Study Site and Period

This experimental research was conducted from April to June 2022 at two locations: (1) the greenhouse and open field facilities of Corteva™ Agriscience in Karawang, West Java, Indonesia,

and (2) the Weed Science Laboratory, Faculty of Agriculture, Universitas Padjadjaran, Sumedang, West Java, Indonesia. These sites were selected to represent controlled and semi-natural tropical environments, allowing for the assessment of herbicide performance under varying conditions.

### Plant Material and Herbicides

Propagules of *E. crassipes* (Mart.) Solms were collected from heavily infested natural water bodies in Karawang, West Java, Indonesia. Uniform plants with a fresh weight of 30–50 g were selected as experimental samples to minimize variability. The herbicides tested were florpyrauxifen benzyl (Loyant®, Corteva Agriscience, Indianapolis, IN, USA), penoxsulam (Clipper®, Dow AgroSciences, Indianapolis, IN, USA), and 2,4-dichlorophenoxyacetic acid (DMA 6®, PT Petrokimia Kayaku, Gresik, Indonesia). Compound fertilizer (NPK 16:16:16, PT Petrokimia Gresik, Indonesia) was used for plant acclimatization prior to herbicide treatment.

### Experimental Design

The study employed a Randomized Complete Block Design (RCBD) with 10 treatments and 3 replications, yielding 30 experimental units. Treatments comprised one untreated control, four rates of florpyrauxifen benzyl (5, 10, 15, and 20 g active ingredient ha<sup>-1</sup>) (Rezkia et al., 2023), and two rates of penoxsulam (6.25 and 12.5 g a.i./ha) were used because they correspond to the recommended label rates and have been validated in previous studies, ensuring effective control of *E. crassipes* without exceeding safe application limits. Higher doses, as used for 2,4-D, were not applied because they are outside the recommended range for penoxsulam (Umiyati et al., 2020), and three 2,4-D rates (400, 500, and 600 g active ingredient ha<sup>-1</sup>) were used (Cerveira et al., 2019). Treatments were randomly assigned within each block using a random number generator to eliminate positional bias. This research was designed as a controlled experimental study, enabling reproducibility through detailed protocols for treatment application and observation. The visual assessment of phytotoxicity was conducted using standardized scoring criteria to minimize subjective bias, although blind evaluation was not implemented.

### Experimental Procedure

Water hyacinth plants were acclimatized for one week in 50 L plastic containers (715 × 275 mm, Lion Star, Jakarta, Indonesia) filled with 20 cm of water and supplemented with 2 g/L of NPK fertilizer. Herbicide solutions were prepared with distilled water and applied at a spray volume of 200 L/ha using a knapsack sprayer (Yamako, Jakarta, Indonesia) equipped with a flat-fan nozzle (TeeJet®, Springfield, IL, USA). Each treatment was applied to six containers, with three maintained under greenhouse conditions and three placed outdoors to evaluate herbicide efficacy under different microclimates. The greenhouse and open-field locations were analyzed as two separate experiments rather than as factors in a factorial design to assess herbicide performance under controlled and natural environmental conditions independently. The overall procedure followed established weed science methodologies for aquatic herbicide testing, with modifications in the acclimatization duration and dose range to suit tropical environmental conditions.

### Observations and Measurements

Phytotoxicity symptoms were visually rated at 1, 3, 5, 7, 9, 11, 13, and 15 days after application (DAA) using a standardized 0–4 scale, where 0 = no visible damage, 1 = slight chlorosis, 2 = moderate chlorosis, 3 = severe necrosis, and 4 = complete plant death. Daily water

loss was measured by refilling each container to a constant depth, allowing estimation of daily water loss (evapotranspiration), which includes both plant transpiration and evaporation from the water surface. Plant samples were harvested at 1, 2, 4, 6, and 8 weeks after application (WAA). For each harvest, one plant was removed from each replicate, resulting in three plants per treatment per harvest. Plants were oven-dried at 80°C for 48 hours (Memmert UN55, Schwabach, Germany), and weighed using an analytical balance (Mettler Toledo, Greifensee, Switzerland) to determine dry weight. The percentage reduction in growth was calculated by comparing the dry weight of treated plants with that of the untreated control. Water physicochemical parameters such as pH, electrical conductivity (EC), dissolved oxygen (DO), and temperature were not measured in this study; this omission is acknowledged as a limitation since these variables may influence herbicide performance under different aquatic conditions.

### Data Analysis

All collected data were subjected to analysis of variance (ANOVA) based on the RCBD model. Significant differences among treatment means were determined using Scott–Knott’s test at a 5% significance level. Data analysis ensured that observed variations were statistically significant and reflected treatment effects rather than random variation.

## RESULTS AND DISCUSSION

### Supporting Observations

During the two-month experiment at Corteva™ Agriscience, Karawang, average temperatures ranged from 24.7 to 29.1°C. Temperature is a key factor influencing the growth of aquatic weeds such as *E. crassipes*, which has an optimum growth range of 28–30°C (Dersseh et al., 2019). Relative humidity ranged from 80.3 to 95.2%, with May–June averaging 88.2% and April averaging 85.2%. Rainfall ranged from 0 to 20.9 mm, and wind speed from 0.07 to 1.50 knots. These warm and humid conditions likely accelerated plant metabolism, enhancing the uptake and translocation of synthetic auxin herbicides (FPB and 2,4-D), which may explain the rapid phytotoxicity observed compared to studies conducted in cooler, temperate climates (Ganie et al., 2017; Ramsey et al., 2005).

### Main Observations

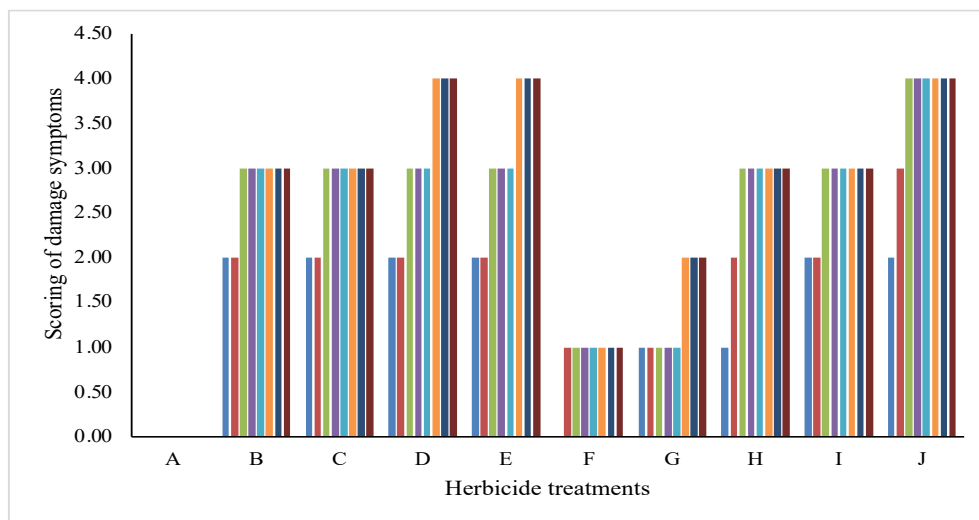
The study evaluated the effects of florpyrauxifen-benzyl, 2,4-dichlorophenoxyacetic acid (2,4-D), and penoxsulam on *E. crassipes*, with 10 treatments and 3 replications. The observed parameters included phytotoxicity, water loss, dry weight, and percentage of damage.

### Phytotoxicity

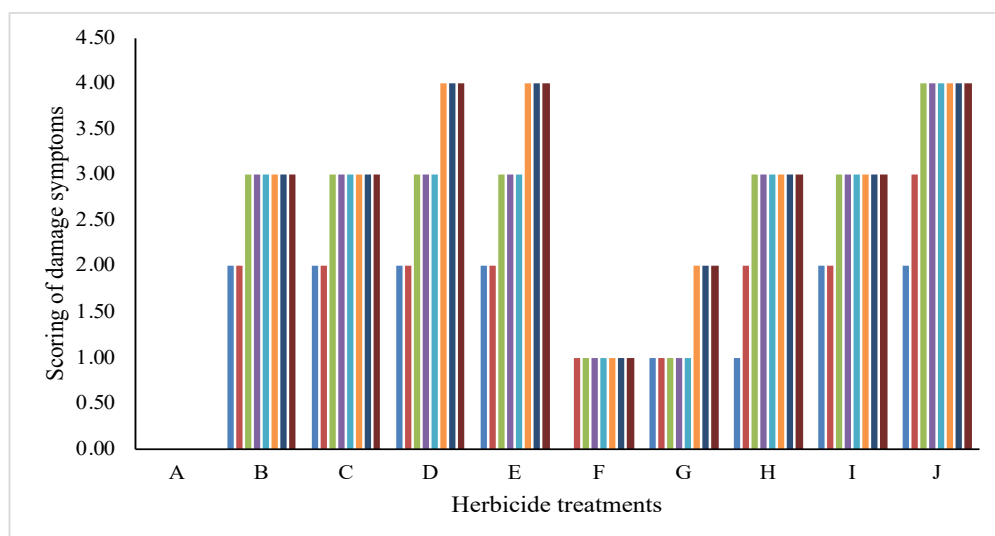
Under outdoor conditions (Figure 1), herbicide application caused varying degrees of phytotoxicity depending on herbicide type and dosage. The maximum injury level (score 4, >75% damage) was observed 5 days after application (DAA) with 2,4-D at 600 g a.i./ha, indicating a rapid auxinic response. Florpyrauxifen benzyl at 15–20 g a.i./ha achieved a similar injury level by 11 DAA, showing strong efficacy at much lower doses. Typical symptoms such as chlorosis, leaf bleaching, curling, and petiole collapse were observed, consistent with the auxin-mimicking mode of action that disrupts cell division and chloroplast integrity (Grossmann, 2007; Grossmann, 2010). In contrast, penoxsulam exhibited slower action, causing only mild injury (score 1) at 15

DAA due to its distinct acetolactate synthase (ALS) inhibition mechanism (Duke & Dayan, 2011).

Under indoor (greenhouse) conditions (Figure 2), similar phytotoxic responses were observed, with florpyrauxifen benzyl and 2,4-D showing pronounced symptoms, while penoxsulam remained less effective throughout the observation period. The comparable trends between indoor and outdoor trials suggest that variations in light intensity and microclimate did not significantly affect herbicide performance. These results indicate that all tested herbicides, particularly florpyrauxifen-benzyl, acted systemically and were rapidly absorbed through the foliage within hours of treatment (Azhari & Khoiri, 2022). Hence, environmental shading had minimal impact on the herbicidal activity under controlled greenhouse conditions.



**Figure 1.** Phytotoxicity scores of water hyacinth (*Eichhornia crassipes*) under outdoor conditions. A. Control, B. FB 5 g a.i./ha, C. FB 10 g a.i./ha, D. FB 15 g a.i./ha, E. FB 20 g a.i./ha, F. P 6.25 g a.i./ha, G. P 12.5 g a.i./ha, H. 2,4-D 400 g a.i./ha, I. 2,4-D 500 g a.i./ha, J. 2,4-D 600 g a.i./ha.



**Figure 2.** Phytotoxicity scores of water hyacinth (*Eichhornia crassipes*) under indoor conditions. A. Control, B. FB 5 g a.i./ha, C. FB 10 g a.i./ha, D. FB 15 g a.i./ha, E. FB 20 g a.i./ha, F. P 6.25 g a.i./ha, G. P 12.5 g a.i./ha, H. 2,4-D 400 g a.i./ha, I. 2,4-D 500 g a.i./ha, J. 2,4-D 600 g a.i./ha.

Herbicide application resulted in varying degrees of damage depending on the type and dose applied. As shown in Figure 1, under outdoor conditions, 2,4-D at 600 g a.i./ha reached the highest injury score of 4 (>75% damage) at 5 days after application (DAA). Observable symptoms such as chlorosis, leaf bleaching, curling, and petiole collapse were consistent with the auxinic mode of action, which disrupts cell division, elongation, and chloroplast integrity (Grossmann, 2007; Prijono et al., 2016). Petiole collapse in particular is likely caused by weakened vascular and structural tissues resulting from impaired cell elongation and turgor loss. In contrast, penoxsulam exhibited the slowest phytotoxic response, causing only mild injury during the same period. This slower action of ALS inhibitors may allow highly invasive, fast-growing species like *E. crassipes* to produce new biomass faster than the herbicide can suppress it, thereby delaying visible injury (Riner et al., 2025).

### Water Loss

Under outdoor conditions, water medium loss differed markedly among herbicide treatments (Table 1), with control plants exhibiting the highest rates of loss throughout the observation period, reflecting unhindered transpiration and surface evaporation. Treatments with high rates of florpyrauxifen-benzyl (15–20 g a.i./ha) showed the greatest reductions in water loss, indicating rapid disruption of normal water relations likely due to accelerated tissue damage and impaired transpiration. Moderate reductions were observed with 2,4-D (400–600 g a.i./ha), while penoxsulam treatments maintained water loss patterns closer to those of the control, consistent with its slower mode of action. These differential responses align with findings that environmental conditions such as temperature and humidity influence herbicide absorption, penetration, and translocation, ultimately affecting plant water use and herbicidal efficacy. High post-application temperatures and favorable humidity may enhance foliar uptake and systemic movement of certain herbicides, leading to more pronounced water-loss suppression in responsive treatments under outdoor conditions than in less responsive ones (Kumar et al., 2023).

**Table 1.** Water medium loss of water hyacinth under outdoor conditions

Treatment	Water Medium Loss of Water Hyacinth (L)							
	1 DAA	2 DAA	3 DAA	4 DAA	5 DAA	6 DAA	7 DAA	8 DAA
A. Control	1.71 <sup>a</sup>	1.71 <sup>a</sup>	1.72 <sup>a</sup>	1.74 <sup>a</sup>	1.78 <sup>a</sup>	1.79 <sup>a</sup>	1.82 <sup>a</sup>	1.86 <sup>a</sup>
B. FB 5g a.i./ha	1.71 <sup>a</sup>	1.70 <sup>a</sup>	1.70 <sup>b</sup>	1.68 <sup>b</sup>	1.66 <sup>c</sup>	1.65 <sup>b</sup>	1.65 <sup>b</sup>	1.62 <sup>b</sup>
C. FB 10g a.i./ha	1.71 <sup>a</sup>	1.69 <sup>b</sup>	1.68 <sup>c</sup>	1.67 <sup>c</sup>	1.62 <sup>d</sup>	1.62 <sup>c</sup>	1.61 <sup>b</sup>	1.59 <sup>c</sup>
D. FB 15g a.i./ha	1.71 <sup>a</sup>	1.69 <sup>b</sup>	1.67 <sup>c</sup>	1.65 <sup>d</sup>	1.59 <sup>e</sup>	1.60 <sup>c</sup>	1.57 <sup>c</sup>	1.54 <sup>d</sup>
E. FB 20g a.i./ha	1.71 <sup>a</sup>	1.69 <sup>b</sup>	1.67 <sup>c</sup>	1.64 <sup>d</sup>	1.58 <sup>f</sup>	1.54 <sup>d</sup>	1.5 <sup>d</sup>	1.47 <sup>e</sup>
F. P 6,25g a.i./ha	1.71 <sup>a</sup>	1.71 <sup>a</sup>	1.70 <sup>b</sup>	1.69 <sup>b</sup>	1.69 <sup>b</sup>	1.69 <sup>b</sup>	1.67 <sup>b</sup>	1.67 <sup>b</sup>
G. P 12,5g a.i./ha	1.71 <sup>a</sup>	1.71 <sup>a</sup>	1.70 <sup>b</sup>	1.68 <sup>b</sup>	1.65 <sup>c</sup>	1.64 <sup>b</sup>	1.63 <sup>b</sup>	1.63 <sup>b</sup>
H. 2,4-D 400g a.i./ha	1.71 <sup>a</sup>	1.71 <sup>a</sup>	1.70 <sup>b</sup>	1.69 <sup>b</sup>	1.67 <sup>b</sup>	1.66 <sup>b</sup>	1.65 <sup>b</sup>	1.64 <sup>b</sup>
I. 2,4-D 500g a.i./ha	1.71 <sup>a</sup>	1.69 <sup>b</sup>	1.68 <sup>c</sup>	1.66 <sup>c</sup>	1.63 <sup>d</sup>	1.62 <sup>b</sup>	1.61 <sup>b</sup>	1.60 <sup>c</sup>
J. 2,4-D 600g a.i./ha	1.71 <sup>a</sup>	1.69 <sup>b</sup>	1.68 <sup>c</sup>	1.65 <sup>c</sup>	1.61 <sup>d</sup>	1.59 <sup>c</sup>	1.58 <sup>c</sup>	1.57 <sup>c</sup>

Note: Mean values followed by the same letter are not significantly different according to Scott–Knott test at the 5% significance level.

Under indoor conditions with more stable temperature and humidity, the overall level of

water loss was lower (Table 2), yet the differential response to herbicides remained evident. High doses of florpyrauxifen-benzyl again produced the greatest decrease in water loss, followed by 2,4-D, while penoxsulam-treated plants maintained a water loss pattern similar to control. Reduced environmental stress enabled clearer expression of herbicide effects on plant water dynamics. Similar studies indicate that transpiration rate, and consequently herbicide uptake and action, can vary with environmental and physiological conditions, as herbicides may influence photosynthetic parameters tightly linked to water use in plants (Dong et al., 2024). Herbicide treatments have been reported to significantly reduce transpiration and water-use efficiency in weeds, indicating that herbicide activity can directly alter plant water dynamics and physiological processes (Negrisoli et al., 2023).

**Table 2.** Water medium loss of water hyacinth under indoor conditions

Treatment	Water Medium Loss of Water Hyacinth (L)							
	1 DAA	2 DAA	3 DAA	4 DAA	5 DAA	6 DAA	7 DAA	8 DAA
A. Control	1.03 <sup>a</sup>	1.04 <sup>a</sup>	1.07 <sup>a</sup>	1.10 <sup>a</sup>	1.15 <sup>a</sup>	1.21 <sup>a</sup>	1.26 <sup>a</sup>	1.31 <sup>a</sup>
B. FB 5g a.i./ha	1.03 <sup>a</sup>	1.02 <sup>b</sup>	1.01 <sup>b</sup>	0.98 <sup>b</sup>	0.93 <sup>b</sup>	0.91 <sup>b</sup>	0.89 <sup>b</sup>	0.88 <sup>b</sup>
C. FB 10g a.i./ha	1.02 <sup>a</sup>	1.01 <sup>b</sup>	0.99 <sup>b</sup>	0.95 <sup>c</sup>	0.91 <sup>b</sup>	0.89 <sup>b</sup>	0.88 <sup>c</sup>	0.86 <sup>c</sup>
D. FB 15g a.i./ha	1.02 <sup>a</sup>	1.01 <sup>b</sup>	0.99 <sup>b</sup>	0.95 <sup>c</sup>	0.89 <sup>b</sup>	0.86 <sup>c</sup>	0.85 <sup>d</sup>	0.83 <sup>d</sup>
E. FB 20g a.i./ha	1.01 <sup>a</sup>	0.98 <sup>c</sup>	0.95 <sup>c</sup>	0.90 <sup>d</sup>	0.84 <sup>d</sup>	0.82 <sup>d</sup>	0.80 <sup>e</sup>	0.79 <sup>e</sup>
F. P 6,25g a.i./ha	1.03 <sup>a</sup>	1.02 <sup>b</sup>	1.00 <sup>b</sup>	0.97 <sup>b</sup>	0.93 <sup>b</sup>	0.92 <sup>b</sup>	0.91 <sup>b</sup>	0.90 <sup>b</sup>
G. P 12,5g a.i./ha	1.02 <sup>a</sup>	1.01 <sup>b</sup>	0.99 <sup>b</sup>	0.96 <sup>b</sup>	0.92 <sup>b</sup>	0.92 <sup>b</sup>	0.90 <sup>b</sup>	0.88 <sup>b</sup>
H. 2,4-D 400g a.i./ha	1.02 <sup>a</sup>	1.02 <sup>b</sup>	1.00 <sup>b</sup>	0.96 <sup>b</sup>	0.91 <sup>b</sup>	0.89 <sup>b</sup>	0.87 <sup>c</sup>	0.86 <sup>c</sup>
I. 2,4-D 500g a.i./ha	1.02 <sup>a</sup>	1.01 <sup>b</sup>	0.99 <sup>b</sup>	0.95 <sup>c</sup>	0.91 <sup>b</sup>	0.87 <sup>c</sup>	0.85 <sup>d</sup>	0.84 <sup>d</sup>
J. 2,4-D 600g a.i./ha	1.02 <sup>a</sup>	0.99 <sup>c</sup>	0.96 <sup>c</sup>	0.91 <sup>c</sup>	0.87 <sup>c</sup>	0.85 <sup>c</sup>	0.83 <sup>d</sup>	0.82 <sup>d</sup>

Note: Mean values followed by the same letter are not significantly different according to Scott–Knott test at the 5% significance level

### Dry Wight

A substantial decrease in dry weight of *E. crassipes* was observed beginning from the first week after herbicide application, with clear differentiation among treatments. As shown in Table 3, florpyrauxifen-benzyl at 15–20 g a.i./ha completely suppressed water hyacinth biomass by the seventh week after application (7 WAA) under outdoor conditions. By contrast, 2,4-D at 400–600 g a.i./ha also eliminated biomass by 7–8 WAA but required substantially higher doses. The dose efficiency ratio indicates that FPB achieved full biomass suppression with 30–40 times less active ingredient than 2,4-D, underscoring its superior efficacy and potential environmental benefits. Conversely, penoxsulam-treated plants maintained higher residual biomass throughout the observation period, indicating weaker herbicidal performance. The pronounced biomass decline following florpyrauxifen benzyl application is associated with its auxin-mimicking mechanism, which accelerates metabolic imbalance, tissue senescence, and eventual cell death (Grossmann, 2007; Chadwick & Mangipudy, 2014; Nio & Lenak, 2014).

In controlled indoor environments, a similar reduction in dry weight was observed (Table 4), although complete biomass suppression occurred slightly later at 8 WAA. Treatments with florpyrauxifen benzyl at 15–20 g a.i./ha again exhibited the highest efficacy, completely inhibiting biomass accumulation, followed by 2,4-D at 400–600 g a.i./ha. In contrast, penoxsulam-treated

plants retained relatively higher biomass levels throughout the study period. The delayed reduction under indoor conditions may be attributed to more stable temperature and humidity, which can slightly influence herbicide uptake and translocation. Nonetheless, the consistent trend across both conditions reinforces the notion that florpyrauxifen benzyl acts rapidly via auxinic pathways, inducing accelerated cellular disorganization and senescence (Grossmann, 2007; Chadwick & Mangipudy, 2014; Nio & Lenak, 2014). Mesocosm experiments demonstrated that florpyrauxifen-benzyl effectively controlled *E. crassipes*, significantly reducing plant growth and biomass within weeks after application, especially at higher herbicide rates (Mudge et al., 2021).

**Table 3.** Dry weight of water hyacinth under outdoor conditions

Treatment	Dry Weight of Weeds (g)							
	1 WAA	2 WAA	3 WAA	4 WAA	5 WAA	6 WAA	7 WAA	8 WAA
A. Control	3.83 <sup>a</sup>	4.72 <sup>a</sup>	5.54 <sup>a</sup>	6.02 <sup>a</sup>	6.27 <sup>a</sup>	6.54 <sup>a</sup>	6.96 <sup>a</sup>	7.21 <sup>a</sup>
B. FB 5g a.i/ha	3.46 <sup>c</sup>	2.94 <sup>b</sup>	2.57 <sup>d</sup>	2.21 <sup>c</sup>	1.68 <sup>c</sup>	1.09 <sup>c</sup>	0.53 <sup>c</sup>	0.00 <sup>d</sup>
C. FB 10g a.i/ha	3.43 <sup>c</sup>	2.75 <sup>c</sup>	2.31 <sup>e</sup>	2.01 <sup>d</sup>	0.95 <sup>e</sup>	0.46 <sup>d</sup>	0.18 <sup>d</sup>	0.00 <sup>d</sup>
D. FB 15g a.i/ha	3.24 <sup>d</sup>	2.61 <sup>c</sup>	2.25 <sup>e</sup>	1.43 <sup>e</sup>	0.89 <sup>e</sup>	0.26 <sup>d</sup>	0.00 <sup>e</sup>	0.00 <sup>d</sup>
E. FB 20g a.i/ha	3.15 <sup>d</sup>	2.28 <sup>c</sup>	1.68 <sup>f</sup>	1.11 <sup>e</sup>	0.67 <sup>e</sup>	0.17 <sup>d</sup>	0.00 <sup>e</sup>	0.00 <sup>d</sup>
F. P 6,25g a.i/ha	3.57 <sup>b</sup>	4.83 <sup>a</sup>	4.24 <sup>b</sup>	3.49 <sup>b</sup>	2.80 <sup>b</sup>	2.24 <sup>b</sup>	1.52 <sup>b</sup>	1.10 <sup>b</sup>
G. P 12,5g a.i/ha	3.38 <sup>c</sup>	3.23 <sup>b</sup>	3.04 <sup>c</sup>	2.76 <sup>c</sup>	2.16 <sup>c</sup>	2.51 <sup>b</sup>	1.68 <sup>b</sup>	0.94 <sup>c</sup>
H. 2,4-D 400g a.i/ha	3.45 <sup>c</sup>	3.16 <sup>b</sup>	2.87 <sup>c</sup>	2.37 <sup>c</sup>	1.79 <sup>c</sup>	0.82 <sup>c</sup>	0.43 <sup>c</sup>	0.00 <sup>d</sup>
I. 2,4-D 500g a.i/ha	3.36 <sup>c</sup>	2.68 <sup>c</sup>	2.45 <sup>d</sup>	1.86 <sup>d</sup>	1.25 <sup>d</sup>	0.63 <sup>c</sup>	0.26 <sup>d</sup>	0.00 <sup>d</sup>
J. 2,4-D 600g a.i/ha	3.15 <sup>d</sup>	2.55 <sup>c</sup>	2.23 <sup>e</sup>	1.73 <sup>d</sup>	1.22 <sup>d</sup>	0.55 <sup>c</sup>	0.03 <sup>c</sup>	0.00 <sup>d</sup>

Note: Mean values followed by the same letter are not significantly different according to Scott–Knott test at the 5% significance level

**Table 4.** Dry weight of water hyacinth under indoor conditions

Treatment	Dry Weight of Weeds (g)							
	1 WAA	2 MSA	1 WAA	4 MSA	1 WAA	6 MSA	7 WAA	8 MSA
A. Control	3.55 <sup>a</sup>	3.64 <sup>a</sup>	3.75 <sup>a</sup>	3.91 <sup>a</sup>	4.05 <sup>a</sup>	4.21 <sup>a</sup>	4.50 <sup>a</sup>	4.93 <sup>a</sup>
B. FB 5g a.i/ha	3.31 <sup>c</sup>	2.61 <sup>c</sup>	2.23 <sup>c</sup>	1.89 <sup>c</sup>	1.70 <sup>c</sup>	1.28 <sup>c</sup>	0.82 <sup>c</sup>	0.00 <sup>d</sup>
C. FB 10g a.i/ha	3.31 <sup>c</sup>	2.60 <sup>c</sup>	2.13 <sup>c</sup>	1.38 <sup>d</sup>	1.12 <sup>c</sup>	0.79 <sup>d</sup>	0.41 <sup>d</sup>	0.00 <sup>d</sup>
D. FB 15g a.i/ha	3.05 <sup>d</sup>	2.53 <sup>c</sup>	1.9 <sup>d</sup>	1.31 <sup>d</sup>	0.66 <sup>e</sup>	0.51 <sup>e</sup>	0.26 <sup>c</sup>	0.00 <sup>d</sup>
E. FB 20g a.i/ha	2.97 <sup>d</sup>	2.36 <sup>c</sup>	1.60 <sup>d</sup>	1.16 <sup>d</sup>	0.93 <sup>f</sup>	0.34 <sup>e</sup>	0.19 <sup>e</sup>	0.00 <sup>d</sup>
F. P 6,25g a.i/ha	3.31 <sup>b</sup>	3.03 <sup>b</sup>	2.49 <sup>b</sup>	2.16 <sup>b</sup>	1.67 <sup>b</sup>	1.28 <sup>b</sup>	0.88 <sup>b</sup>	0.32 <sup>b</sup>
G. P 12,5g a.i/ha	3.31 <sup>c</sup>	3.03 <sup>b</sup>	2.49 <sup>c</sup>	2.16 <sup>c</sup>	1.67 <sup>c</sup>	1.28 <sup>c</sup>	0.88 <sup>c</sup>	0.32 <sup>c</sup>
H. 2,4-D 400g a.i/ha	3.30 <sup>c</sup>	2.51 <sup>c</sup>	2.18 <sup>c</sup>	1.81 <sup>c</sup>	1.32 <sup>d</sup>	1.11 <sup>c</sup>	0.43 <sup>d</sup>	0.00 <sup>d</sup>
I. 2,4-D 500g a.i/ha	3.21 <sup>c</sup>	2.42 <sup>c</sup>	1.77 <sup>d</sup>	1.38 <sup>d</sup>	1.05 <sup>e</sup>	0.75 <sup>d</sup>	0.42 <sup>d</sup>	0.00 <sup>d</sup>
J. 2,4-D 600g a.i/ha	3.07 <sup>d</sup>	2.33 <sup>c</sup>	1.71 <sup>d</sup>	1.25 <sup>d</sup>	0.55 <sup>f</sup>	0.41 <sup>e</sup>	0.31 <sup>d</sup>	0.00 <sup>d</sup>

Note: Mean values followed by the same letter are not significantly different according to Scott–Knott test at the 5% significance level

Under outdoor conditions (Table 5), all herbicide treatments significantly increased water hyacinth damage compared with the control. Florpyrauxifen-benzyl at 15–20 g a.i./ha and 2,4-D at 600 g a.i./

ha achieved complete mortality (100%) by 7 WAA, whereas lower doses reached the same level at 8 WAA. Under outdoor conditions (Table 5), all herbicide treatments significantly increased water hyacinth damage compared with the control. Florpyrauxifen-benzyl at 15–20 g a.i./ha and 2,4-D at 600 g a.i./ha achieved complete mortality (100%) by 7 WAA, whereas lower doses reached the same level at 8 WAA. In contrast, penoxsulam exhibited the lowest efficacy, causing only 84–90% damage by the end of the observation period. The faster damage progression outdoors is likely attributable to higher light intensity and temperature, which enhance transpiration and thereby accelerate herbicide uptake and systemic action (Priyono et al., 2016). These results highlight FPB as a highly effective and environmentally favorable alternative, achieving rapid and complete suppression at substantially lower doses compared with conventional herbicides. Field research conducted in a tropical lake also demonstrated that florpyrauxifen-benzyl effectively controlled *E. crassipes*, achieving up to 100% growth reduction at doses of 15 g a.i./ha within 42 days after application, indicating strong herbicidal activity against this invasive aquatic weed (Kurniadie et al., 2023).

### Percentage of Damage

Meanwhile, under indoor conditions (Table 6), a similar trend was observed, although complete mortality under florpyrauxifen benzyl and 2,4-D occurred uniformly at 8 WAA. Differences in temperature and light availability slightly delay the onset of herbicidal effects compared with outdoor conditions, but the overall pattern of dose-dependent damage remained consistent.

**Table 5.** Percentage of damage of water hyacinth under outdoor conditions

Treatment	Weed Damage Percentage (%)							
	1 WAA	2 MSA	1 WAA	4 MSA	1 WAA	6 MSA	7 WAA	8 MSA
A. Control	0.00 <sup>c</sup>	0.00 <sup>d</sup>	0.00 <sup>c</sup>	0.00 <sup>c</sup>	0.00 <sup>c</sup>	0.00 <sup>d</sup>	0.00 <sup>c</sup>	0.00 <sup>d</sup>
B. FB 5g a.i/ha	9.43 <sup>b</sup>	42.57 <sup>b</sup>	53.71 <sup>c</sup>	63.05 <sup>c</sup>	72.99 <sup>c</sup>	83.21 <sup>b</sup>	92.39 <sup>c</sup>	100.0 <sup>a</sup>
C. FB 10g a.i/ha	11.49 <sup>b</sup>	46.07 <sup>a</sup>	58.06 <sup>b</sup>	66.89 <sup>b</sup>	84.84 <sup>a</sup>	93.04 <sup>a</sup>	97.41 <sup>b</sup>	100.0 <sup>a</sup>
D. FB 15g a.i/ha	15.12 <sup>a</sup>	48.96 <sup>a</sup>	59.41 <sup>b</sup>	76.33 <sup>a</sup>	86.02 <sup>a</sup>	96.07 <sup>a</sup>	100.0 <sup>a</sup>	100.0 <sup>a</sup>
E. FB 20g a.i/ha	17.37 <sup>a</sup>	55.35 <sup>a</sup>	69.56 <sup>a</sup>	81.61 <sup>a</sup>	89.19 <sup>a</sup>	97.36 <sup>a</sup>	100.0 <sup>a</sup>	100.0 <sup>a</sup>
F. P 6,25g a.i/ha	6.55 <sup>b</sup>	8.37 <sup>c</sup>	23.47 <sup>d</sup>	42.09 <sup>d</sup>	55.23 <sup>d</sup>	65.64 <sup>c</sup>	78.15 <sup>d</sup>	84.69 <sup>c</sup>
G. P 12,5g a.i/ha	11.51 <sup>b</sup>	36.82 <sup>b</sup>	45.15 <sup>c</sup>	54.10 <sup>c</sup>	65.47 <sup>c</sup>	62.06 <sup>c</sup>	75.91 <sup>d</sup>	86.92 <sup>b</sup>
H. 2,4-D 400g a.i/ha	9.55 <sup>b</sup>	38.05 <sup>b</sup>	48.24 <sup>c</sup>	60.49 <sup>c</sup>	71.25 <sup>c</sup>	87.44 <sup>b</sup>	93.81 <sup>c</sup>	100.0 <sup>a</sup>
I. 2,4-D 500g a.i/ha	11.88 <sup>b</sup>	47.65 <sup>a</sup>	55.78 <sup>b</sup>	69.12 <sup>b</sup>	79.95 <sup>b</sup>	90.32 <sup>b</sup>	96.86 <sup>b</sup>	100.0 <sup>a</sup>
J. 2,4-D 600g a.i/ha	17.49 <sup>a</sup>	50.10 <sup>a</sup>	59.80 <sup>b</sup>	71.19 <sup>b</sup>	80.49 <sup>b</sup>	91.48 <sup>b</sup>	99.52 <sup>a</sup>	100.0 <sup>a</sup>

Note: Mean values followed by the same letter are not significantly different according to Scott–Knott test at the 5% significance level

Penoxsulam again demonstrated the weakest performance, with the lowest damage percentages throughout the study period. These results confirm that auxin-mimicking herbicides maintain high effectiveness even under reduced light intensity, as their systemic mode of action ensures consistent translocation within plant tissues (Priyono et al., 2016). Rezkia et al. (2023) reported that penoxsulam reduced the growth of *E. crassipes* by approximately 75%, whereas

florpyrauxifen-benzyl achieved up to 100% growth reduction within 42 days after application. The reduction in water loss and dry biomass after the application of florpyrauxifen-benzyl (FPB) can be explained by its mechanism of action as a synthetic auxin mimic. Once applied, FPB is absorbed through leaves or shoots and translocated via both the xylem and phloem to meristematic and vascular tissues (Tangahu, 2024). Inside plant cells, FPB binds with high affinity to auxin receptors such as AFB5 and other members of the TIR1/AFB family, thereby inducing the overactivation of auxin-regulated genes. This hormonal overactivation disrupts the balance of other plant hormones, including ethylene and abscisic acid (ABA), and promotes the accumulation of reactive oxygen species (ROS). These physiological disturbances lead to uncontrolled cell elongation, abnormal curvature of leaves and petioles, and general tissue distortion (Gao et al., 2022).

**Table 6.** Percentage of damage of water hyacinth under indoor conditions

Treatment	Weed Damage Percentage (%)							
	1 WAA	2 MSA	1 WAA	4 MSA	1 WAA	6 MSA	7 WAA	8 MSA
A. Control	0.00 <sup>c</sup>	0.00 <sup>c</sup>	0.00 <sup>c</sup>	0.00 <sup>d</sup>	0.00 <sup>e</sup>	0.00 <sup>e</sup>	0.00 <sup>d</sup>	0.00 <sup>d</sup>
B. FB 5g a.i/ha	5.87 <sup>b</sup>	28.49 <sup>a</sup>	40.25 <sup>a</sup>	51.80 <sup>b</sup>	57.88 <sup>e</sup>	69.60 <sup>c</sup>	81.74 <sup>b</sup>	100.0 <sup>a</sup>
C. FB 10g a.i/ha	6.66 <sup>b</sup>	28.59 <sup>a</sup>	43.12 <sup>a</sup>	64.77 <sup>a</sup>	72.22 <sup>c</sup>	80.91 <sup>b</sup>	90.82 <sup>a</sup>	100.0 <sup>a</sup>
D. FB 15g a.i/ha	13.98 <sup>a</sup>	30.36 <sup>a</sup>	48.90 <sup>a</sup>	66.40 <sup>a</sup>	83.76 <sup>a</sup>	87.89 <sup>a</sup>	94.30 <sup>a</sup>	100.0 <sup>a</sup>
E. FB 20g a.i/ha	16.22 <sup>a</sup>	35.13 <sup>a</sup>	56.98 <sup>a</sup>	70.40 <sup>a</sup>	76.92 <sup>b</sup>	91.98 <sup>a</sup>	95.85 <sup>a</sup>	100.0 <sup>a</sup>
F. P 6,25g a.i/ha	3.99 <sup>b</sup>	13.70 <sup>b</sup>	22.81 <sup>b</sup>	34.40 <sup>c</sup>	47.15 <sup>f</sup>	54.66 <sup>d</sup>	70.08 <sup>c</sup>	87.84 <sup>c</sup>
G. P 12,5g a.i/ha	6.64 <sup>b</sup>	16.92 <sup>b</sup>	33.41 <sup>b</sup>	44.90 <sup>b</sup>	58.56 <sup>e</sup>	69.44 <sup>c</sup>	80.36 <sup>b</sup>	93.51 <sup>b</sup>
H. 2,4-D 400g a.i/ha	6.90 <sup>b</sup>	31.15 <sup>a</sup>	41.57 <sup>a</sup>	53.74 <sup>b</sup>	67.46 <sup>d</sup>	73.57 <sup>c</sup>	90.37 <sup>a</sup>	100.0 <sup>a</sup>
I. 2,4-D 500g a.i/ha	9.47 <sup>a</sup>	33.69 <sup>a</sup>	52.69 <sup>a</sup>	64.76 <sup>a</sup>	74.16 <sup>c</sup>	82.06 <sup>b</sup>	90.59 <sup>a</sup>	100.0 <sup>a</sup>
J. 2,4-D 600g a.i/ha	13.45 <sup>a</sup>	36.10 <sup>a</sup>	54.52 <sup>a</sup>	68.14 <sup>a</sup>	86.47 <sup>a</sup>	90.31 <sup>a</sup>	93.10 <sup>a</sup>	100.0 <sup>a</sup>

Note: Mean values followed by the same letter are not significantly different according to Scott–Knott test at the 5% significance level

Moreover, FPB causes severe damage to the vascular system, resulting in the collapse of xylem and phloem integrity. This vascular disruption not only hinders water and nutrient transport, reducing transpiration due to impaired water delivery and stomatal closure induced by elevated ABA levels, but also effectively traps the herbicide within the target tissues, ensuring meristem death and preventing regrowth. Consequently, photosynthesis declines, severely limiting the accumulation of structural biomass. In fast-growing aquatic weeds such as *E. crassipes*, this manifests as tissue dehydration, loss of turgidity, reduced dry weight, and visible necrosis following FPB treatment (Rezki et al., 2023). These physiological disruptions collectively explain the consistent suppression of growth observed across experimental conditions. Because the herbicidal effect occurs through systemic vascular collapse rather than surface absorption alone, florpyrauxifen-benzyl performance tends to remain stable even when environmental factors fluctuate.

The consistency of results between indoor and outdoor experiments indicates that the herbicidal efficacy of florpyrauxifen-benzyl remains high under varying environmental conditions, such as light intensity, temperature, and water quality, despite the compound being designed to degrade relatively quickly in water for environmental safety. While environmental factors can

influence the absorption and activity of synthetic auxin herbicides, no significant differences were observed between indoor and outdoor treatments in this study, suggesting that FPB maintains both stability and effectiveness under diverse tropical microclimates. These findings agree with reports showing that florypyrauxifen-benzyl exhibits high efficacy across different field application conditions. However environmental variability can affect uptake and translocation in some weed species (Galikovski et al., 2024). Moreover, studies have demonstrated that spray volume and weather conditions, including temperature and humidity, can influence herbicide performance on aquatic weeds such as *Salvinia molesta* (Howell et al., 2023), and similar interactions have been reported for other synthetic auxins, such as 2,4-D against resistant species (Ganie & Jhala, 2017). Collectively, these results confirm that florypyrauxifen-benzyl at 15–20 g a.i./ha provides consistent and effective control of *E. crassipes* under variable tropical conditions in Indonesia.

These findings provide new insight into the comparative performance of florypyrauxifen-benzyl, 2,4-D, and penoxsulam in controlling *Eichhornia crassipes* under tropical conditions. The present study demonstrates that florypyrauxifen-benzyl can achieve effective suppression of water hyacinth at substantially lower application rates while also revealing its influence on plant water dynamics and biomass reduction, highlighting its potential as a more efficient and environmentally favorable herbicide for aquatic weed management.

## CONCLUSION

Florypyrauxifen-benzyl effectively controlled *E. crassipes* under Indonesian tropical conditions, with optimal performance at 15 g a.i./ha, which was comparable to 2,4-D at 600 g a.i./ha. Increasing the dose to 20 g a.i./ha did not significantly improve efficacy, indicating that 15 g a.i./ha is the minimum effective dose. In contrast, penoxsulam showed limited effectiveness. These findings identify florypyrauxifen-benzyl as a low-dose and effective alternative for water hyacinth control.

## AUTHOR CONTRIBUTION

**M.F.C.** conducted the research, analyzed the data, and prepared the initial manuscript; **P.E. & M** refined and wrote the manuscript for publication; **D.K.** supervised, revised, and provided guidance throughout the research.

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## CONFLICT OF INTEREST

The authors declare no competing financial interests or personal relationships that could have influenced this work.

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