

ORIGINAL RESEARCH

Selective Herbicide Combinations Sustain Early *Eucalyptus pellita* Growth and Soil Microbial Abundance During Plantation Land Preparation in South Sumatra

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ABSTRACT

Background: Herbicide application during land preparation is routine in tropical industrial plantation forestry, yet its simultaneous effects on soil biology, weed cover, and tree growth are rarely evaluated together.

Objective: This study assessed the effects of herbicide combinations applied during land preparation on weed cover, early growth of *Eucalyptus pellita* (height and stem diameter), and total soil microbial abundance at PT Musi Hutan Persada, Muara Enim, South Sumatra, Indonesia, as an implementation of IFCC Indicator 7.2.8 on minimising chemical pesticide use.

Methods: A Completely Randomized Design with four treatments and four replications (16 plots of 360 m²) compared P1 (control), P2 (indaziflam+iodosulfuron, 250 g ha⁻¹), P3 (glyphosate 3 L ha⁻¹ + indaziflam+iodosulfuron), and P4 (glyphosate 3 L ha⁻¹ + metsulfuron-methyl 300 g ha⁻¹ + indaziflam+iodosulfuron), analysed by one-way ANOVA with η^2 effect sizes, LSD separation, Pearson correlation, and principal component analysis.

Results: Herbicide treatment significantly reduced weed cover ($F(3,12)=18.42$, $p<0.001$, $\eta^2=0.82$), with suppression of 27.9%, 45.9%, and 68.1% in P2, P3, and P4, but did not significantly affect height, stem diameter, or microbial abundance (all $p>0.05$). Microbial abundance stayed about four orders of magnitude above the 10² CFU g⁻¹ degradation threshold of Regulation No. 07/2006, and all plots were classified as not degraded.

Conclusion: Selective, well-timed herbicide combinations can control weeds effectively without compromising early *E. pellita* growth or soil microbial abundance, supporting sustainable plantation management under IFCC Indicator 7.2.8.

Introduction

Industrial plantation forests (*Hutan Tanaman Industri*, HTI) are a strategic component of Indonesia's forestry sector, supplying the fibre that underpins the national pulp and paper industry while easing harvesting pressure on natural forests. In South Sumatra, *Eucalyptus pellita* F. Muell. has become the principal planted species because of its rapid juvenile growth, broad tolerance of acidic and nutrient-poor mineral soils, and high biomass productivity.^{1,2} The economic viability of these plantations depends heavily on the establishment phase, when uniform survival and early growth determine final stand productivity.³ During this window, spontaneous

weed regeneration is the dominant biological constraint, because weeds compete directly with young trees for light, water, nutrients, and growing space.^{3,4}

Chemical weed control remains the most operationally efficient and cost-effective option at concession scale, and pre-plant applications of soil-residual and foliar herbicides are routinely used during land preparation to manage both pre-emergent and post-emergent flora.⁵ The active ingredients evaluated here represent complementary modes of action: indaziflam inhibits cellulose biosynthesis and provides long-residual control of annual grasses;⁵ iodosulfuron and metsulfuron-methyl are acetolactate-synthase (ALS) inhibitors;⁶ and glyphosate inhibits 5-

enolpyruvylshikimate-3-phosphate synthase (EPSPS) in the shikimate pathway.⁷ Combining complementary chemistries broadens the spectrum of control and is a recognised anti-resistance strategy, although mixture efficacy and the risk of crop phytotoxicity depend strongly on rate and timing.^{6,8}

Intensive herbicide use, however, carries environmental and toxicological risk, particularly for the soil biological properties that sustain nutrient cycling and plant health. Global assessments now rank pesticide loading as a planetary-scale pressure on soils and water resources,^{9,10} and glyphosate has been associated with shifts in soil microbial activity and nutrient turnover.^{11,12} Counterbalancing this, diverse microbial communities frequently display resilience to herbicide residues, in some cases metabolising them as carbon substrates and maintaining stable population levels in the short term.^{13,14} Physical disturbance during site preparation can also influence microbial counts more strongly than direct chemical toxicity.¹⁵

Within Indonesia, herbicide monitoring is anchored by two frameworks. The Ministry of Environment Regulation (*PermenLH*) No.07 of 2006 on Procedures for Measuring Soil Quality Criteria for Biomass Production sets a minimum biological threshold of $\geq 10^2$ colony-forming units per gram (CFU g⁻¹) of soil for total microbial abundance, below which a soil is deemed biologically degraded. In parallel, the Indonesian

Forestry Certification Cooperation (IFCC) — the national system endorsed by the Programme for the Endorsement of Forest Certification (PEFC) — requires under Indicator 7.2.8 that operators minimise chemical pesticide use and monitor its environmental consequences. Demonstrating compliance therefore requires field evidence that herbicide regimes control weeds effectively without degrading soil quality or plantation performance.¹⁰

Despite an extensive literature, weed-control efficacy, tree-growth response, and soil biological response have generally been studied in isolation rather than within a single operational experiment, and evidence from tropical industrial plantation forests — as distinct from annual cropping systems — remains scarce.^{8,11} Few studies translate their findings into the specific regulatory and certification language that plantation managers must satisfy.

The study area is presented in Figure 1. The purpose of this study was to evaluate the effects of four herbicide regimes applied during land preparation on weed cover, early growth (height and stem diameter) of *E. pellita*, and total soil microbial abundance at PT Musi Hutan Persada, Muara Enim Regency, South Sumatra, Indonesia, and to interpret the results as field evidence for the implementation of IFCC Indicator 7.2.8 under operational plantation conditions.

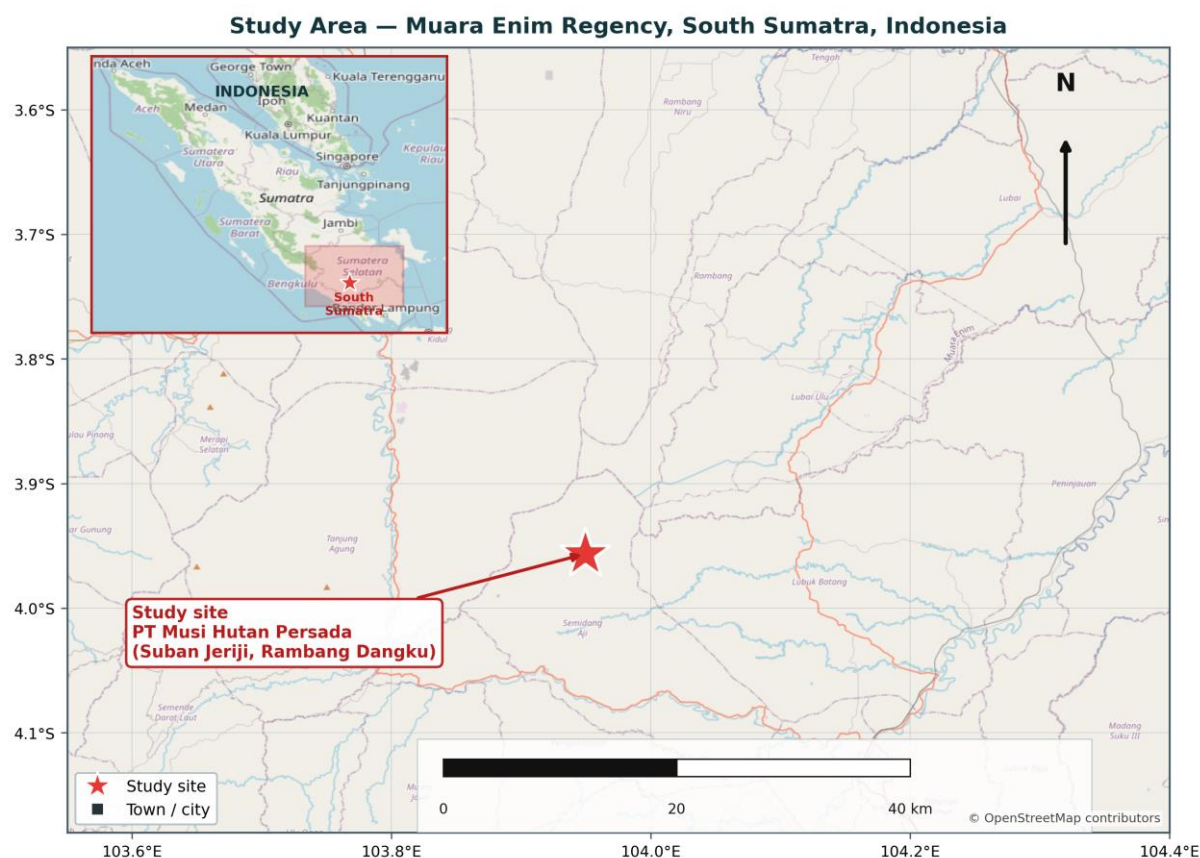


Figure 1. Study area map showing the experimental site at PT Musi Hutan Persada (Suban Jeriji, Rambang Dangku District, Muara Enim Regency, South Sumatra, Indonesia; 3°57'23.209" S, 103°56'58.062" E). Inset: location of South Sumatra Province within Indonesia.

Materials and Methods

Study design and setting

This study was an operational-scale environmental field experiment combining agronomic growth monitoring with soil biological assessment. The conceptual pathway linking herbicide application to weed, tree, and microbial receptors is summarised in Figure 2, which frames the analysis within the IFCC 7.2.8 and PermenLH 07/2006 sustainability context.

As illustrated in Figure 1, the study was conducted in the plantation area and the Research & Development

Division Laboratory of PT Musi Hutan Persada, Region 1 Suban Jeriji, Rambang Dangku District, Muara Enim Regency, South Sumatra Province, Indonesia (3°57'23.209" S; 103°56'58.062" E; approximately 156 m above sea level). The concession covers 286,914.65 ha, of which more than 100,000 ha are in active production. The site has been used continuously for *E. pellita* cultivation since 2013 and had completed three five-year rotations by 2024.¹⁶ The experiment ran from July to December 2024 in an open post-harvest area being prepared for a new *E. pellita* clone-047 stand.

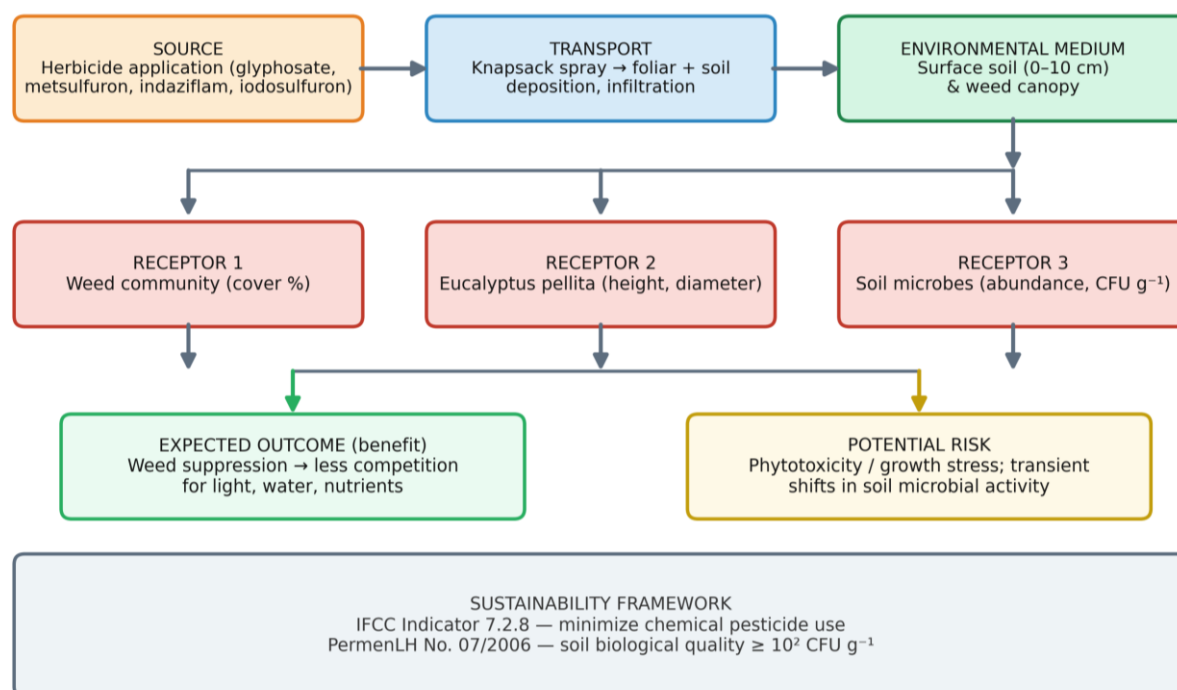


Figure 2. Conceptual framework of the herbicide pathway during land preparation, linking the source through transport and the soil/weed medium to three receptors within the IFCC 7.2.8 and PermenLH 07/2006 frame.

Materials, samples, and data sources

A Completely Randomized Design (CRD) was used with four herbicide treatments and four replications, giving 16 experimental units, the spatial arrangement of which is shown in Figure 3. Each plot measured 9 m × 40 m (360 m²) on flat terrain (<5% slope). The treatments were: P1, control (no herbicide); P2, Esplanade (indaziflam + iodosulfuron) at 250 g ha⁻¹; P3, Kleen Up (glyphosate) at

3 L ha⁻¹ + Esplanade at 250 g ha⁻¹; and P4, Kleen Up (glyphosate) at 3 L ha⁻¹ + Metafuron (metsulfuron-methyl) at 300 g ha⁻¹ + Esplanade at 250 g ha⁻¹. Herbicides were premixed before transfer to a knapsack sprayer and applied uniformly along planting lines. *E. pellita* clone 047 was planted after most weeds showed visible mortality, at 3 m × 2 m spacing (40 plants per plot). The full characteristics of the experimental units are summarised in Table 1.

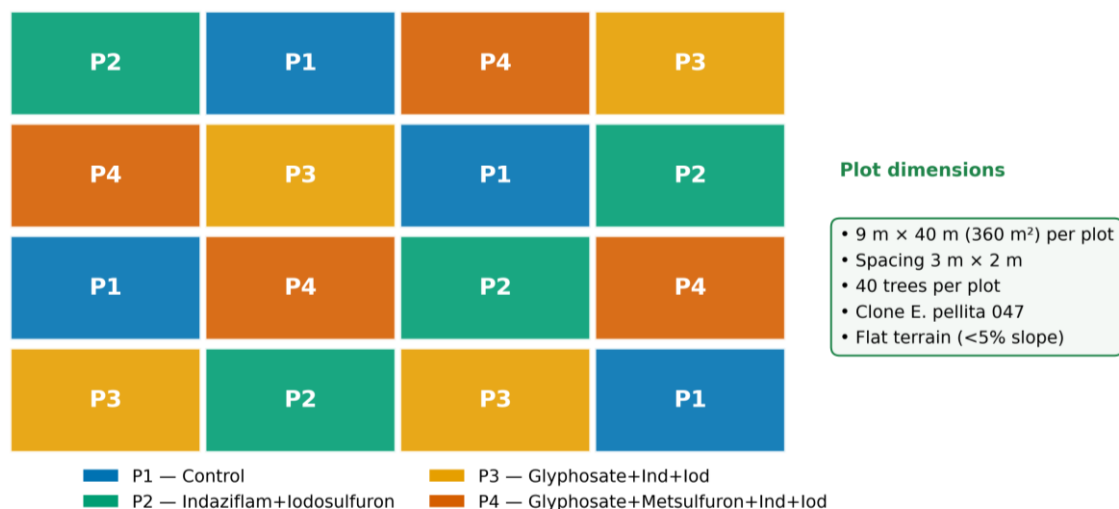


Figure 3. Completely Randomized Design layout of the 16 experimental plots (four treatments $\times$ four replications; 9 m $\times$ 40 m each).

Experimental variables and analytical procedures

Plant height and stem diameter were recorded for all 40 plants per plot (saturated sampling) at 1 and 2 months after planting (MAP). Height was measured from the soil surface to the highest growing point with a graduated measuring stick; stem diameter was measured 10 cm above the soil surface with a digital caliper.

Weed cover was assessed with a 1 m $\times$ 1 m quadrat placed randomly within each plot. Each quadrat was divided into four equal sub-sections (A–D), each representing 25% of the area; a fully covered sub-section scored 25% and a half-covered sub-section 12.5%. Total weed cover per plot was the sum of sub-section values. Assessments were made at 1 and 2 MAP, and weed suppression was calculated as the percentage reduction in weed cover relative to the control.

Total soil microbial abundance was determined by the standard plate count method on Nutrient Agar (NA), incubated for 48 h at 28 °C, and expressed as CFU g⁻¹ soil. Because enumeration used a single medium, the metric represents culturable heterotrophic bacterial abundance, which is the operational basis of the PermenLH No. 07/2006 criterion; it is termed total microbial abundance for consistency with that regulation. Soil was sampled at 2 MAP from 0–10 cm as a composite of five sub-samples per plot, and results were evaluated against the regulatory minimum of $\geq 10^2$ CFU g⁻¹.¹⁷

All glassware and media were sterilised by autoclaving (121 °C, 15 min). Nutrient Agar was prepared to the manufacturer's specification and verified for sterility using non-inoculated blank plates incubated alongside the samples. Serial dilutions were prepared in sterile physiological saline, and plates yielding 30–300 colonies were counted to remain within the reliable counting range. Field equipment was cleaned between plots, soil samples were transported in labelled sterile

bags under cool conditions, and counts were performed in duplicate with the mean retained. Caliper and measuring-stick readings were standardised by a single trained operator to minimise observer bias.

Results were benchmarked against the Indonesian biological soil-quality standard (PermenLH No.07/2006; $\geq 10^2$ CFU g⁻¹) and discussed in the context of international evidence on pesticide loading and soil health.^{9,10}

Data analysis

Data were analysed in R (v4.3.1). Normality and homogeneity of variance were checked with the Shapiro–Wilk and Levene tests, and the assumptions were satisfied ($p > 0.05$). The plot (not the individual tree) was the experimental unit, so growth variables were reduced to plot means before analysis and one composite value per plot entered the microbial analysis. Each parameter was subjected to one-way analysis of variance (ANOVA); the eta-squared (η^2) effect size was computed as the ratio of between-treatment to total sum of squares. Where the omnibus F was significant, means were separated with the protected Least Significant Difference (LSD) test and reported with a compact-letter display. Associations among parameters were quantified with Pearson correlation, and treatment structure was explored with principal component analysis (PCA) on standardised parameter means (prcomp, scaling = TRUE). Three study-appropriate indices were derived: Weed Control Efficacy (WCE, % reduction versus control), a Microbial Quality Index (MQI = $\log_{10}[\text{observed CFU} / 10^2 \text{ threshold}]$), and an Integrated Plantation Sustainability Index (IPSI), the mean of min–max normalised WCE and MQI. The significance level was $\alpha = 0.05$ and exact p-values are reported to three decimals. No human or animal subjects were involved; the research was conducted with the permission of PT Musi Hutan Persada.

Table 1. Characteristics of the experimental units and herbicide treatments at the study site.

Treatment	Herbicide composition	Application rate	Reps	Plot area (m ²)	Planting
P1 – Control	None (untreated)	–	4	360	Jul 2024
P2	Indaziflam + iodosulfuron	250 g ha ⁻¹	4	360	Jul 2024
P3	Glyphosate + indaziflam + iodosulfuron	3 L ha ⁻¹ + 250 g ha ⁻¹	4	360	Jul 2024
P4	Glyphosate + metsulfuron-methyl + indaziflam + iodosulfuron	3 L ha ⁻¹ + 300 g ha ⁻¹ + 250 g ha ⁻¹	4	360	Jul 2024

Results

General site conditions

A total of 16 plots were established across four treatments in the post-harvest land-preparation area at PT Musi Hutan Persada (Figure 1; Figure 3). The site had relatively flat topography and carried residual logging debris from the previous rotation, including wood residues, branches, and surface organic matter. Natural weed vegetation had established sporadically, and initial weed cover during land preparation was low (approximately 5–10%), which facilitated effective site preparation and reduced the herbicide rates required. The characteristics of the 16 experimental units, including treatment composition, application rates, and sampling details, are summarised in Table 1.

Early growth: plant height

As detailed in Table 2 and illustrated in Figure 4a, one-way ANOVA showed that herbicide treatment had no significant effect on plant height at either 1 MAP

($F(3,12)=2.14$, $p=0.148$, $\eta^2=0.35$) or 2 MAP ($F(3,12)=1.87$, $p=0.188$, $\eta^2=0.32$). At 1 MAP, mean height in herbicide-treated plots ranged from 33.57 cm (P4) to 38.35 cm (P2), all below the control mean of 42.42 cm. The same ordering persisted at 2 MAP, where treated plots ranged from 55.39 cm (P4) to 60.08 cm (P3) against 63.74 cm in the control. Height increased consistently from 1 to 2 MAP in every treatment (Figure 4a).

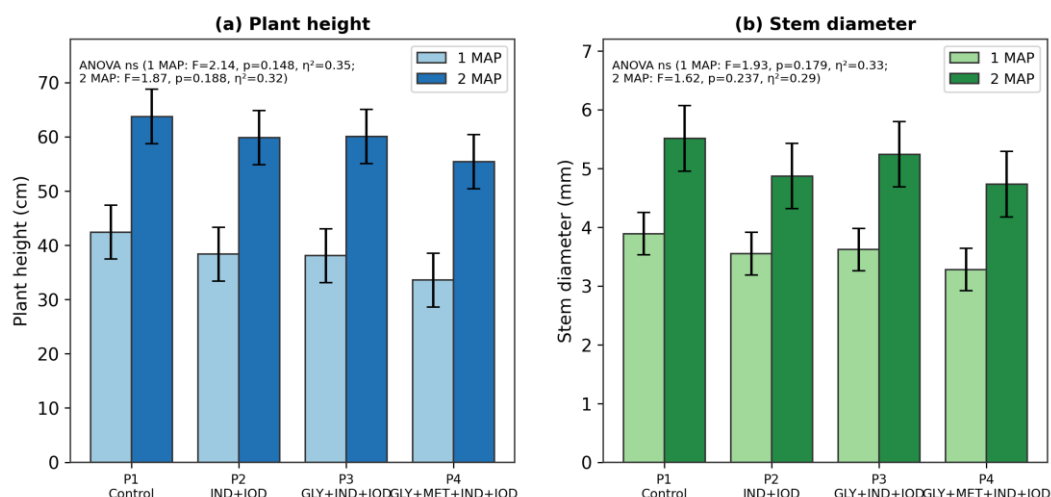
Early growth: stem diameter

Stem diameter likewise did not differ significantly among treatments at 1 MAP ($F(3,12)=1.93$, $p=0.179$, $\eta^2=0.33$) or 2 MAP ($F(3,12)=1.62$, $p=0.237$, $\eta^2=0.29$), as shown in Table 2 and Figure 4b. At 2 MAP, mean stem diameter ranged from 4.73 mm (P4) to 5.51 mm (control), with P2 and P3 intermediate at 4.87 and 5.24 mm. The moderate effect sizes ($\eta^2 = 0.29$ – 0.35 across growth variables) indicate that treatment accounted for only a minor, non-significant share of growth variance during the monitoring period.

Table 2. Mean ($\pm$ SD) plant height and stem diameter of *Eucalyptus pellita* at 1 and 2 months after planting (MAP), with one-way ANOVA F, p, and η^2 effect sizes.

Treatment	Height 1 MAP (cm)	Height 2 MAP (cm)	Diam. 1 MAP (mm)	Diam. 2 MAP (mm)
P1	42.42 $\pm$ 4.94	63.74 $\pm$ 5.00	3.89 $\pm$ 0.36	5.51 $\pm$ 0.56
P2	38.35 $\pm$ 4.94	59.86 $\pm$ 5.00	3.55 $\pm$ 0.36	4.87 $\pm$ 0.56
P3	38.07 $\pm$ 4.94	60.08 $\pm$ 5.00	3.62 $\pm$ 0.36	5.24 $\pm$ 0.56
P4	33.57 $\pm$ 4.94	55.39 $\pm$ 5.00	3.28 $\pm$ 0.36	4.73 $\pm$ 0.56
F (p; η^2)	2.14 (0.148; 0.35)	1.87 (0.188; 0.32)	1.93 (0.179; 0.33)	1.62 (0.237; 0.29)

Early growth of *Eucalyptus pellita* under herbicide treatments

**Figure 4.** Early growth of *Eucalyptus pellita*: (a) plant height and (b) stem diameter at 1 and 2 MAP (means $\pm$ SD; all ANOVA non-significant).

Weed cover and suppression

In contrast to the growth variables, herbicide treatment significantly affected weed cover at 2 MAP ($F(3,12)=18.42$, $p<0.001$, $\eta^2=0.82$; $LSD_{5\%} = 8.73$), as presented in Table 3 and Figure 5. Weed cover declined monotonically from 63.75% in the control (P1, group d) to 45.94% in P2 (group c), 34.50% in P3 (group b), and

20.31% in P4 (group a); all four treatments differed significantly by the LSD test. As shown by the suppression curve in Figure 5, weed suppression relative to the control was 27.9% (P2), 45.9% (P3), and 68.1% (P4), the last being the highest recorded. The large effect size ($\eta^2 = 0.82$) confirms that herbicide regime explained the great majority of variation in weed cover.

Table 3. Weed cover and suppression at 2 MAP, with protected LSD mean separation and ANOVA statistics.

Treatment	Weed cover (%) $\pm$ SD	Suppression (%)	Group
P1	63.75 $\pm$ 8.56	–	d
P2	45.94 $\pm$ 8.56	27.9	c
P3	34.50 $\pm$ 8.56	45.9	b
P4	20.31 $\pm$ 8.56	68.1	a
F (p; η^2)	18.42 (<0.001; 0.82)	$LSD_{5\%} = 8.73$	–

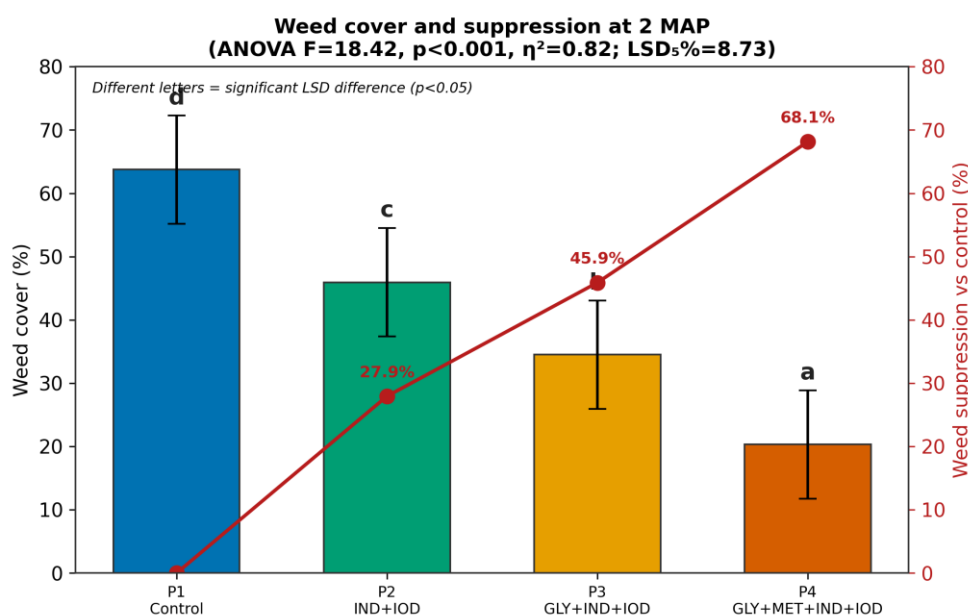


Figure 5. Weed cover (bars, $\pm$ SD) and weed suppression relative to control (line) at 2 MAP. Different letters denote significant LSD differences ($p < 0.05$).

Soil microbial abundance

Total soil microbial abundance at 2 MAP did not differ significantly among treatments ($F(3,12)=1.48$, $p=0.270$, $\eta^2=0.27$), as detailed in Table 4 and Figure 6. Mean counts ranged from 6.1×10^5 CFU g^{-1} (P4) to 1.4×10^6

CFU g^{-1} (P2), with the control at 9.4×10^5 CFU g^{-1} . As Figure 6 shows, every treatment exceeded the PermenLH No. 07/2006 threshold of 10^2 CFU g^{-1} by approximately four orders of magnitude, so all plots were classified as 'not degraded'; the corresponding Microbial Quality Index ranged from 3.79 (P4) to 4.15 (P2).

Table 4. Total (culturable) soil microbial abundance at 2 MAP and degradation status against PermenLH No. 07/2006, with ANOVA statistics and the Microbial Quality Index (MQI).

Treatment	Microbial abundance (CFU g^{-1})	Threshold	Status	MQI
P1	9.4×10^5	$\geq 10^2$	Not degraded	3.97
P2	1.4×10^6	$\geq 10^2$	Not degraded	4.15
P3	8.3×10^5	$\geq 10^2$	Not degraded	3.92
P4	6.1×10^5	$\geq 10^2$	Not degraded	3.79
F (p; η^2)	1.48 (0.270; 0.27)	–	–	–

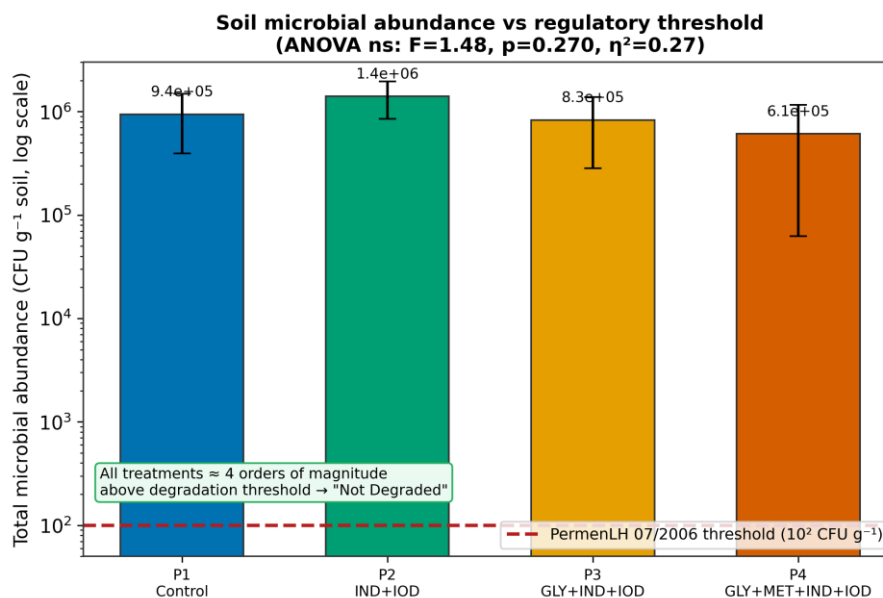


Figure 6. Total (culturable) soil microbial abundance (log scale, means $\pm$ SD) versus the PermenLH No. 07/2006 biological -quality threshold (10^2 CFU g⁻¹).

Multivariate structure and environmental indices

At the treatment-mean level, and as visualised in the correlation matrix of Figure 9 and summarised in Table 5, weed cover correlated positively and significantly with early height ($r=0.95$, $p=0.048$) and positively with stem diameter ($r=0.77$), indicating that the same intensity gradient that suppressed weeds also slightly reduced early tree vigour. Microbial abundance was weakly and non-significantly associated with the growth variables. Principal component analysis (Figure 8) resolved two

interpretable axes: PC1 explained 81.5% of the variance and represented a combined vigour-and-weed-suppression gradient separating the control from P4, whereas PC2 explained 17.3% and was dominated by microbial abundance, so that PC1 and PC2 together accounted for 98.8% of total variance. The Integrated Plantation Sustainability Index, which balances weed-control benefit against microbial retention (Figure 7), was highest for P2 (IPSI = 0.70) and intermediate for P3 and P4.

Table 5. Pearson correlations among treatment-mean parameters ($n = 4$).

Pearson r	Height	Diameter	Weed cover	Microbial
Height	1.00	0.90	0.95	0.43
Diameter	0.90	1.00	0.77	0.00
Weed cover	0.95	0.77	1.00	0.53
Microbial	0.43	0.00	0.53	1.00

Integrated environmental performance indices by treatment (min-max normalized)

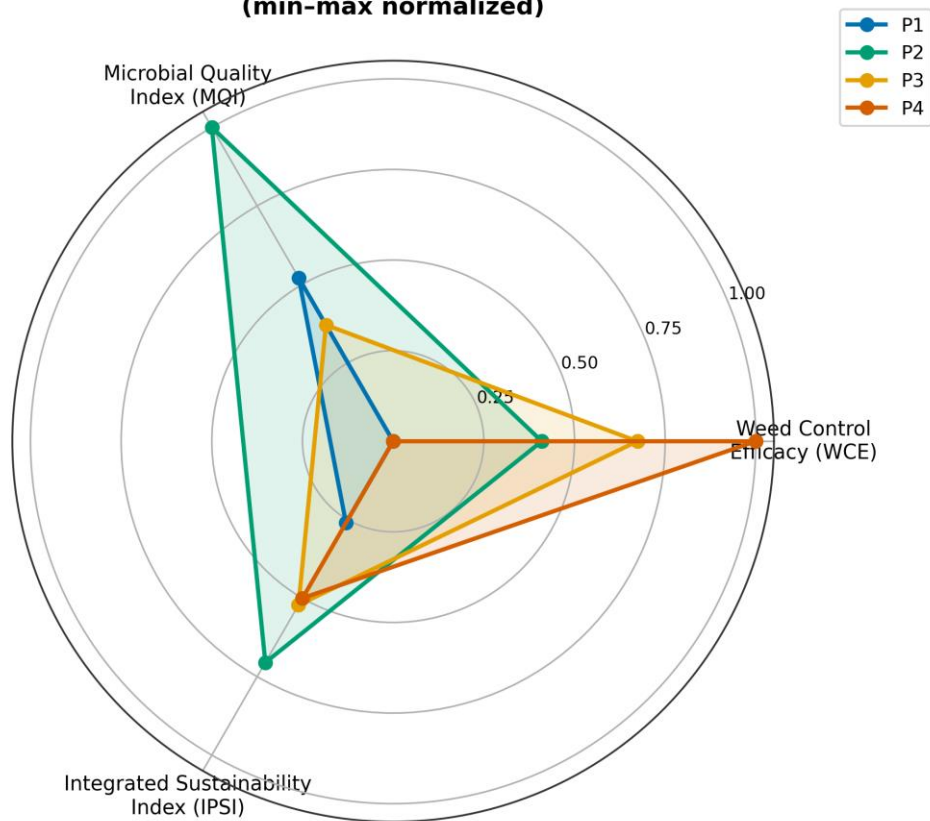


Figure 7. Integrated environmental performance indices (WCE, MQI, IPSI) by treatment (min-max normalised).

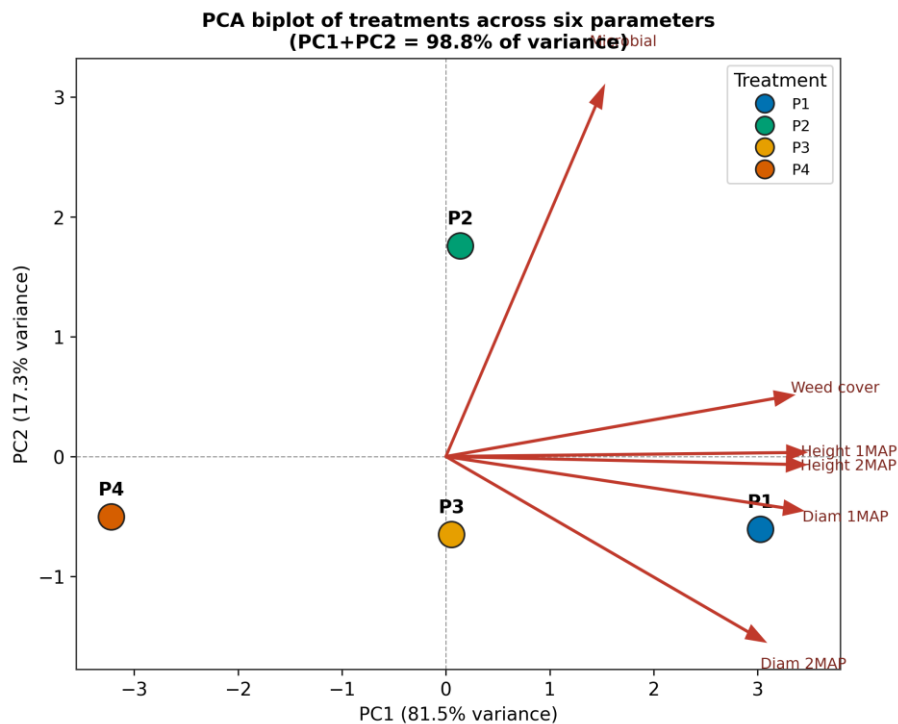


Figure 8. PCA biplot of the four treatments across six parameters; PC1 and PC2 jointly explain 98.8% of the variance.

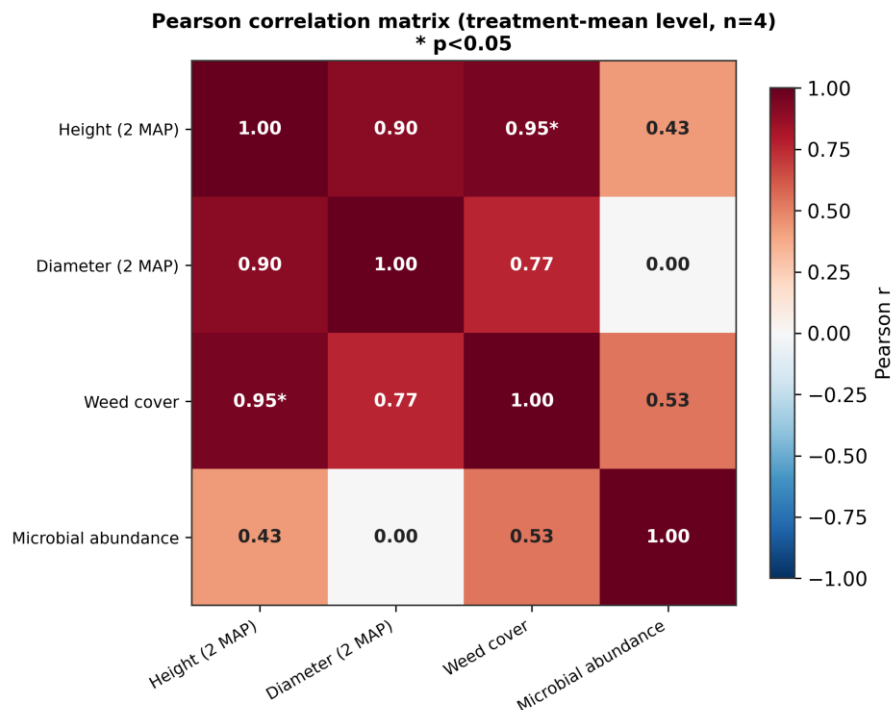


Figure 9. Pearson correlation matrix among treatment-mean parameters (n = 4; * p < 0.05).

Discussion

This study evaluated four operational herbicide regimes applied during land preparation at PT Musi Hutan Persada and integrated their effects on weed cover, early *E. pellita* growth, and soil microbial abundance. The central result is consistent and policy-relevant: herbicide treatment produced a strong, graded reduction in weed cover (up to 68.1% suppression in the four-component mixture, P4) while leaving early tree growth and soil microbial abundance statistically unchanged, with microbial counts remaining about four orders of magnitude above the Indonesian degradation threshold. In effect, the weed-control benefit was achieved without a measurable soil-biological cost over the two-month monitoring window.

The graded weed response is mechanistically coherent. Treatment P2 (indaziflam + iodosulfuron) reduced weed cover by 27.9%, consistent with cellulose-biosynthesis inhibition by indaziflam and ALS inhibition by iodosulfuron suppressing germination and early growth.⁵ Adding glyphosate in P3 raised suppression to 45.9% by introducing EPSPS inhibition and broad post-emergent activity,^{7,11} and the further addition of metsulfuron-methyl in P4 lifted suppression to 68.1%, reflecting the broader spectrum delivered by four complementary modes of action.^{6,8} The progressive gain with mixture complexity, and the large effect size ($\eta^2 = 0.82$), indicate a near-additive to synergistic interaction among the active ingredients, in line with contemporary recommendations to combine chemistries for spectrum and resistance management.⁶

The absence of a significant growth response merits careful interpretation. Although height and stem

diameter were consistently, but non-significantly, lower in herbicide-treated plots than in the control, this pattern is best read as a mild, transient physiological signal rather than a damaging effect. Sub-lethal herbicide exposure can temporarily inhibit photosynthesis, cell division, and nutrient uptake,⁷ and stacking several active ingredients can intensify early stress in young plants. The moderate effect sizes ($\eta^2 = 0.29–0.35$) and the uniform increase in growth from 1 to 2 MAP nevertheless indicate strong tolerance and rapid recovery in *E. pellita* at operational rates.^{3,4} The significant positive correlation between weed cover and early growth across treatments ($r = 0.95$, $p = 0.048$) is informative: the control retained both the most weeds and the most vigorous trees, implying that the same herbicide-intensity gradient that suppressed weeds also exerted a slight, manageable drag on early tree vigour — a trade-off that managers can optimise through rate and timing.

A second mechanism shaping the results is the low initial weed pressure (5–10%) and the mechanical soil disturbance along planting lines, which together acted as a physical weed-control measure. This integrated chemical-plus-mechanical effect improved the availability of light, water, and nutrients and is likely to have compressed the growth differences among treatments. Such integration is precisely the kind of reduced-input strategy promoted by sustainable-management frameworks.^{2,3}

The soil microbial findings are consistent with the resilience reported for diverse microbial communities. The lack of significant treatment differences, despite a four-fold range in mean counts, indicates sufficient functional redundancy to buffer short-term herbicide exposure.^{12,13} The relatively higher abundance in P2 is

plausibly linked to carbon and nitrogen inputs from decomposing weed biomass following herbicide-induced mortality, a recognised short-term stimulation pathway, and herbicide-treated soils can even act as reservoirs of beneficial, tolerant bacteria.¹⁴⁻¹⁸ The slightly lower counts in P3 and P4 are more likely attributable to physical site-preparation disturbance — soil inversion and transient changes in moisture, aeration, and temperature — than to direct chemical toxicity, echoing tillage-driven microbial dynamics reported elsewhere.^{11,15}

From a risk perspective, the results are reassuring but bounded in time. All treatments maintained microbial populations far above the PermenLH No. 07/2006 threshold, indicating no short-term biological soil degradation and no acute ecological hazard at the rates applied, consistent with recent evidence that individual herbicides exert minimal, transient effects on soil bacterial structure and function.^{13,19} However, the global literature cautions that cumulative and increasingly diverse pesticide loading is a growing pressure on soils, capable of impairing microbial functions over time.^{9,10} Long-term, diversity-resolved monitoring therefore remains essential.²⁰

These findings translate directly into the regulatory and certification context that motivated the study. The results provide field evidence supporting IFCC Indicator 7.2.8: selective, well-timed herbicide use, combined with mechanical disturbance and favourable operational scheduling, controlled weeds effectively while preserving soil biological integrity.¹³ Because initial weed cover was low when site preparation followed harvesting promptly, appropriate operational timing emerges as a practical lever to reduce herbicide rates — delivering both environmental and economic benefits. An integrated weed-management strategy that couples chemical and mechanical control is therefore recommended to lower herbicide dependence in future rotations while remaining consistent with IFCC sustainability principles.⁴

Placing these results alongside Indonesian and tropical plantation studies reinforces their external validity. Efficacy gains from metsulfuron-based mixtures observed in Southeast Asian perennial-crop systems parallel the graded suppression recorded here,^{6,8} while the maintenance of high culturable microbial counts is consistent with the resilience of diverse tropical and temperate soil communities.^{12,13,15} The convergence of these independent lines of evidence strengthens confidence that the weed-control benefit reported here is reproducible and that the short-term soil-biological neutrality is not an artefact of a single site.

The economic dimension of IFCC Indicator 7.2.8 also deserves emphasis. Because prompt post-harvest scheduling kept initial weed cover low (5–10%), lower herbicide volumes were sufficient to achieve operationally acceptable control. For a concession exceeding 100,000 ha in active production, even modest per-hectare reductions in herbicide rate translate into

substantial savings in chemical, labour, and compliance costs, while simultaneously reducing the environmental loading that certification frameworks seek to minimise.^{9,10}

Future monitoring should move beyond abundance to community structure and function. A diversity-resolved design — combining high-throughput amplicon sequencing of bacterial and fungal communities with enzymatic and nutrient-cycling assays, sampled repeatedly across a full rotation — would detect sub-lethal, cumulative shifts that a two-month plate-count metric cannot.^{17,20} Incorporating soil physicochemical covariates and weed-species composition would further sharpen mechanistic attribution and support a quantitative, rotation-scale sustainability assessment for IFCC reporting.

The study has several strengths. It integrates weed-control efficacy, tree-growth response, and soil biological response within a single operational CRD experiment at a working concession, giving high external validity. It applies a strengthened analytical framework — effect sizes, multivariate ordination, and purpose-built environmental indices — that goes beyond conventional single-parameter reporting. And it interprets results in the explicit language of Indonesian soil-quality regulation and PEFC-endorsed certification.

Several limitations should temper interpretation. The monitoring period was short (two months after planting), so the conclusions concern early establishment and short-term soil response rather than full-rotation outcomes. Total culturable abundance by plate count captures the heterotrophic bacterial fraction but not community composition or functional diversity, which respond more sensitively to chemical stress.¹⁷ Soil physicochemical covariates and weed-species composition were not measured, limiting mechanistic attribution. Finally, the experiment represents a single site and one season; multi-site, multi-season replication would be needed before generalising across the diversity of South Sumatran plantation soils.

Conclusion

Herbicide treatment during land preparation significantly reduced weed cover ($F(3,12)=18.42$, $p<0.001$, $\eta^2=0.82$) but had no significant effect on early *E. pellita* height, stem diameter, or total soil microbial abundance. The four-component mixture (glyphosate + metsulfuron-methyl + indaziflam + iodosulfuron, P4) achieved the highest weed suppression (68.1% relative to the control), and all treatments maintained microbial populations roughly four orders of magnitude above the $\geq 10^2$ CFU g⁻¹ biological-degradation threshold of PermenLH No. 07/2006, indicating no short-term soil degradation. These results show that selective, well-timed herbicide combinations can control weeds effectively without compromising early growth or soil microbial abundance. An integrated chemical-and-mechanical weed-management strategy is recommended to reduce herbicide dependence in future

rotations, and long-term, diversity-resolved soil monitoring is advised to confirm sustainability under repeated application, consistent with IFCC Indicator 7.2.8.

Declarations

Ethical Approval. This study involved no human participants, animals, or sensitive personal data; environmental sampling was conducted with the permission of PT Musi Hutan Persada.

Conflict of Interest. PT Musi Hutan Persada provided site access and laboratory facilities but had no role in the analysis, interpretation, or the decision to publish.

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Data Availability. The plot-level dataset and the analysis scripts supporting the findings of this study are available from the corresponding author on reasonable request.

Use of Artificial Intelligence. During the preparation of this work, the authors did not use any generative AI tools. The authors reviewed and edited the content and take full responsibility for the final manuscript.

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