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Vertical distribution of weed seed bank in three-year-old oil palm plantations

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Abstract. *Sitinjak L, Purba E, Hanum C, Siregar LAM. 2025. Vertical distribution of weed seed bank in three-year-old oil palm plantations. Biodiversitas 26: 3571-3579.* Soil may contain millions of weed seeds from different species. Understanding the soil seed bank is crucial for making effective and sustainable weed management plans. This study provides novel insight into vertical seed bank distribution in tropical agroecosystems, a topic that remains underexplored, so that it can prevent reinfestation and dependence on herbicides. In this study, we measured the species composition and vertical distribution of the weed seed bank in agricultural soil. We collected soil samples using a 9 cm diameter soil core in a zigzag pattern. Samples were taken at depths of 0-5 cm, 5-10 cm, 10-15 cm, and 15-20 cm, with four duplicates per depth. At Universitas Sumatera Utara, Indonesia, each sample was spread in sterile trays filled with sand and incubated in a greenhouse. Seedling emergence was monitored for eight weeks. No new seedlings appeared in the last two weeks. A vegetation survey at the sampling site was also included. Data were analyzed using a non-factorial, randomized complete block design. Seedling emergence was significantly affected by soil depth. The highest seed bank density was at 5-10 cm (51.50 seedlings, 43.45%), followed by 0-5 cm (48.75 seedlings, 41.14%), 10-15 cm (12.50 seedlings, 10.55%), and 15-20 cm (5.75 seedlings, 4.85%). In total, the seed bank produced 354 seedlings. *Asystasia gangetica* was the most common, with 131 individuals. Aboveground vegetation yielded 256 individuals, predominantly *Persicaria odorata* (38 individuals, 14.84%). Most weed propagules accumulated in the top 10 cm of soil. Thus, shallow tillage, competitive cover crops, and well-timed herbicide applications targeting seedling flushes should focus on this layer. To prevent replenishment of the seed bank and curb invasive or resistant species, seasonal adjustments and routine observation of the seed bank and vegetation are vital. This integrated, site-specific approach supports more effective and sustainable weed control in agricultural systems.

Keywords: Seed bank, species dominance, vertical distribution, weed composition, weed management

INTRODUCTION

Indonesia is the world's largest palm oil producer, with 45.5 million metric tons produced in 2022-2023. Malaysia follows with 18.8 million tons (USDA Foreign Agricultural Service 2024). In 2022, Indonesia produced 46.8 million tons from 15.3 million hectares of plantations (Central Bureau of Statistics 2023). Despite increasing production, productivity is limited by factors such as fertilization (Esteban et al. 2024), pests and diseases (Hussian et al. 2025), and, in particular, weeds (Formaglio et al. 2020). Weeds compete for space, light, nutrients, and water, causing yield losses of 20-80% (Soltani et al. 2016). They persist and thrive because perennial systems, such as oil palm, offer undisturbed soils, making management particularly challenging. Surveys in oil palm fields have identified numerous troublesome species, including *Chromolaena odorata*, *Mikania micrantha, Melastoma malabathricum, Asystasia gangetica*, *Lantana camara*, and *Imperata cylindrica* (Benvenuti and Mazzoncini 2019). Creeping broadleaf weeds, such as *Micania micrantha* and *A. gangetica,* can significantly reduce yields, with *A. gangetica* and *Cynodon dactylon* among the dominant species (Khalil 2016). The soil seed bank, which contains seeds, stolon's, tubers, and rhizomes, is crucial for weed emergence (Kumar et al. 2024). Seed bank accumulation is encouraged by stable canopy cover and minimal soil disturbance, making control harder (Oreja et al. 2025). Recent studies have shown that crop variety, management, soil, and climate all influence seed bank dynamics (Baraibar and Knudsen 2024).

The vertical distribution of seed banks in the soil profile is a crucial yet understudied component of seed bank dynamics. According to Luo et al. (2023), seeds are dispersed both horizontally and vertically, and their depth affects agronomic and ecological results. Importantly, seeds that are more deeply buried permit longer dormancy and population persistence, as they provide ecological protection against light, desiccation, and predators (Moravcová et al. 2022). In contrast, seeds closer to the surface are exposed to light, temperature, and moisture conditions that are more conducive to germination (Luo et al. 2023). Furthermore, over time, both seed mobility and viability are influenced by soil structure and biota (Nakabayashi and Leubner-Metzger 2021).

Understanding the vertical seed bank profile enables the development of focused, long-term management plans from an agronomic perspective (Formaglio et al. 2020). Most viable seeds are found in the upper layers of soil. Therefore, shallow tillage or mulching can efficiently deplete the seed bank while causing minimal soil disturbance. In contrast, extensive tillage can bring latent seeds to the surface. This may lead to new infestations (Simard et al. 2021). The vertical seed profile also affects the effectiveness of manual weeding, herbicide application, and cover crop establishment in tropical perennial plantations with minimal tillage (Oreja et al. 2025).

Despite extensive research on weed seed banks, little is known about their vertical distribution in tropical agricultural systems. Furthermore, few studies have examined the species composition in relation to depth, which is critical for depth-targeted weed control.

The vertical distribution of weed seed banks in tropical perennial cropping systems, such as oil palm, remains poorly understood. This is significant both ecologically and agronomically. Most of the research has focused on annual temperate systems, which differ in soil dynamics and management (Baraibar and Knudsen 2024). Oil palm plantations, where soils remain mostly intact for decades, may show distinct vertical stratification of seed banks. This pattern can impact management effectiveness (Oreja et al. 2025). In perennial systems, weed seeds may stratify within the soil. This results from minimal soil disturbance, dense canopy, and lengthy cropping cycles. These factors shape both management outcomes and weed emergence patterns (Diop et al. 2024). Seeds in surface layers directly contribute to infestations. In contrast, seeds buried deeper may stay dormant longer and avoid eradication (Tao et al. 2022). Seed transport and viability can differ in tropical soils due to unique biological activity (Alfonzetti et al. 2023). Such circumstances promote seed stratification, which affects interventions like tillage, herbicide use, and cover crop establishment. Therefore, vertical profiling of the seed bank is essential in perennial systems (Alfonzetti et al. 2023).

We hypothesized that weed seed density decreases with soil depth, and that certain species dominate the upper layers. Thus, the purpose of this study was to measure the species composition and vertical distribution of the weed seed bank in oil palm plantations. It is anticipated that the results will help develop more sustainable and efficient weed management techniques suited to tropical perennial cropping systems by revealing the distribution of weed seeds throughout the soil profile.

MATERIALS AND METHODS

Sample collection: Soil seed bank

At an elevation of 179 meters above sea level, in the Sei Putih Estate, Galang Sub-district, Deli Serdang, South Sumatera, Indonesia, soil seed bank samples were taken from an oil palm plantation owned by PTP Nusantara II, which is immature (the plants are three years old and have not yet produced any yield). The Plantation is located at coordinates 3.497061°N and 98.906359°E. Since 2021, oil palm has been grown on the property. The following in Figure 1 is a seed bank sampling map.

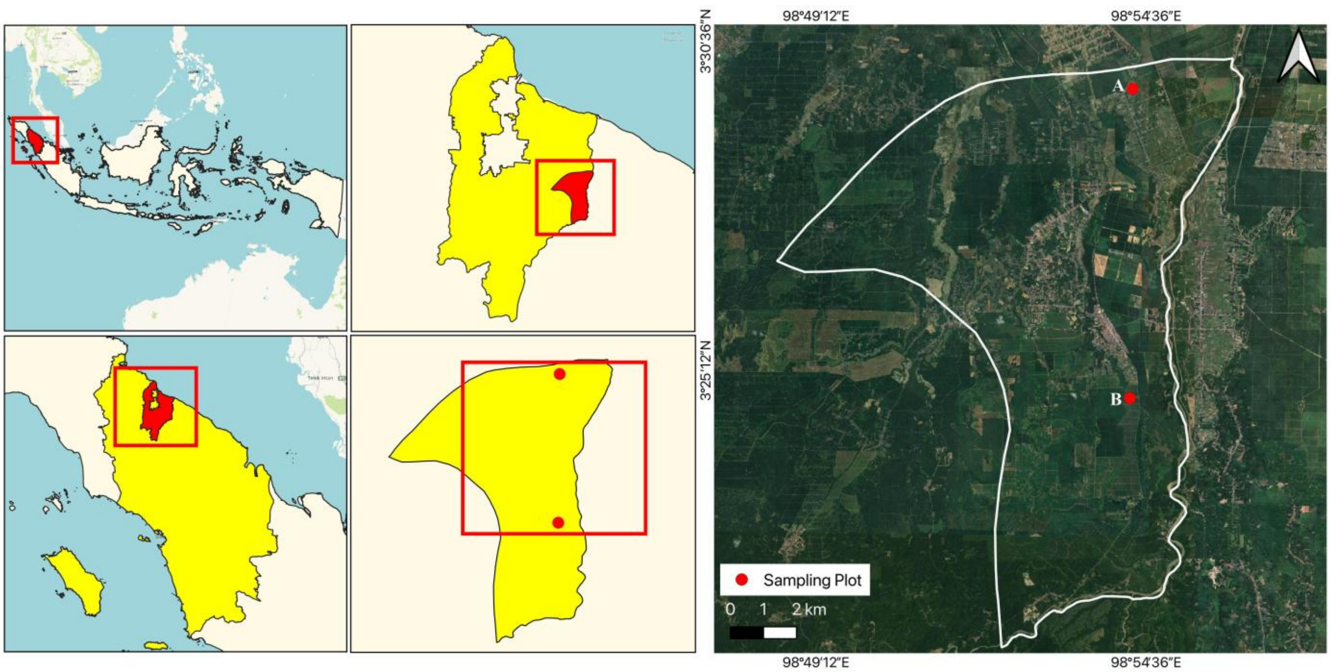

Figure 1. Site map showing seed bank sampling locations. A. Location of the plantation site, B. Location of the seed bank sampling block

Table 1. Climatological data of the study site

Data	Average/month/year	
	2023	2024
Rainfall (mm)	227.58	178.67
Rainy Days (days)	19	20.17
Temperature (ºC)	25.7	26.15
Humidity (%)	88.67	88,58
Duration of irradiation (%)	64.25	64.45
Dominant wind direction (º)	217.5	233.18
Wind speed (m/s)	0.53	0.46

Source: ECMWF ERA 5 Data, North Sumatera Climatological Station 30 December 2024

The following meteorological data were observed during the sampling period, which was characterized by comparatively high rainfall (Table 1). To collect soil samples for seed bank examination, we began by using a cylindrical soil core sampler with a diameter of 9 cm and a total depth of 20 cm. From each soil core, four segments representing depths of 0-5 cm, 5-10 cm, 10-15 cm, and 15-20 cm were separated for further analysis. Determining the depth of this seed bank refers to research that has been carried out by predecessors, including (Ramesh et al. 2017).

Each soil sample had a surface area of 63.59 cm² at each depth. This depth stratification was informed by Oreja et al. (2025), who found that most weed seeds are concentrated in the upper soil layers (0-5 cm), though some may become buried deeper due to biotic activity and soil disturbance. Similarly, Shiferaw et al. (2018) used stratified layers to assess the vertical distribution of soil seed banks. Sampling across the study plot followed a zigzag pattern. At each location, three soil cores were combined to produce one composite sample at each depth. This was repeated four times, resulting in a total of 16 seed bank samples (four seed bank samples at each depth).

Vegetation analysis

An initial vegetation survey was conducted to describe the current weed flora at the research location prior to soil seed bank sampling 50×50 cm (Guo et al. 2022) quadrats were randomly positioned four times in each replication to evaluate the vegetation. All weed species were identified, and their respective numbers were noted inside each quadrat. Field observations were used to identify species, species identification was conducted based on morphological characteristics using standard, with the aid of books (Ghazali et al. 2016). Cellphones, and internet resources (such as Google Search) to verify names as needed. The fresh weight was then determined by harvesting and weighing all the aboveground weed biomass in each quadrat. To calculate the dry weight, the samples were oven-dried for three days at 70°C (Kolla et al. 2021). Lastly, species composition and dominance in the aboveground vegetation were determined by calculating the Sum Dominance Ratio (SDR) and weed density (individuals per square meter).

Experimental design and data analysis

Soil seed bank depth, a single-factor treatment was used to set up the experiment. There were four levels: 0-5 cm, 5-10 cm, 10-15 cm, and 15-20 cm. Four duplicates of each treatment made. Both descriptive and inferential methods were employed in the study. A Randomized Complete Block Design (RCBD) was used for inferential analysis. At the same time, vegetation survey data and the composition of emerging seedlings from the soil seed bank were analyzed using descriptive methods. The RCBD's linear statistical model was written as follows: Yik = μ+αi+(α)i+Σik.

Analysis of Variance (ANOVA) was used to examine the obtained data at a significance threshold of α: 0.05. Duncan's Multiple Range Test (DMRT) was used to compare means and identify statistically significant differences among soil depth treatment as indicated by the ANOVA results (Wiraguna et al. 2023). IBM SPSS Statistics software, version 26, was used for all statistical analyses (Bhardwaj and Kaushik 2024).

Seed bank germination in the greenhouse

A germination experiment was conducted at Universitas Sumatera Utara in a greenhouse with controlled conditions: an average temperature of 32°C, an average light intensity of 14242 Lux (if available), and an average moisture level of 45%. Sterilized sand, heated at 70°C in a metal drum and cooled for a full day, was used as the planting medium. Soil seed bank samples collected from the field were loosened and planted. Sterile sand was spread evenly in trays (25×36×5 cm) to a depth of 3.5-4 cm. Soil seed bank samples were distributed on the sand surface according to the designated depth treatments. Trays were irrigated twice daily and kept covered for the first week to maintain humidity, promote germination, and prevent contamination from external seeds or propagules.

Parameters for observation

The seedling emergence method, which involved spreading soil samples in trays, keeping them moist in a greenhouse, and checking on them every two weeks for eight weeks or until no new seedlings appeared, was used to evaluate seed bank germination (Padonou et al. 2022). The percentage of germination of the entire seed bank and the average number of seeds that germinated were computed.

By integrating the species and counts of emerging seedlings from the seed bank trays with the results of the initial vegetation survey, the seed bank composition was assessed. To identify the species, number, density, and dominant weed species, a final vegetation examination was conducted on each tray once no additional seedlings had appeared. Observations were conducted at two-week intervals. Observations were made when the seedbank sprouts were two, four, six, and eight Weeks After Sowing (WAS).

RESULTS AND DISCUSSION

The dispersion of weed seed banks was found to be considerably impacted by soil depth. While densities at >10-15 cm and >15-20 cm fell precipitously (12.5 and 5.75, or 15.4% altogether), seed density at 0-10 cm depth reached 84.6% of the total (48.7 at 0-5 cm and 51.5 at >5-10 cm).

Surface seeds germinate more readily because of improved light, oxygen, and temperature (Padonou et al. 2022), but many seeds accumulate in the upper 0-10 cm because of restricted vertical movement and shallow soil disturbance (Zhang et al. 2025). Less favorable conditions and less biological activity may be the cause of lower densities below 10 cm (Carvalho et al. 2019).

These results underscore the importance of controlling the top seed bank, which has the most significant potential for weed regeneration. Weed emergence and persistence can be efficiently suppressed by surface seed-targeting practices such as mulching or limited tillage (Bajwa et al. 2019).

Weed seed bank density was highest at the 0-5 cm depth during early observations (2-6 WAS), but by 8 WAS, it had shifted to >5-10 cm, whereas densities at >10-15 cm and >15-20 cm stayed low throughout, according to data in Table 2 and Figure 1. Due to shallow tillage and restricted vertical movement, seeds initially accumulated in the surface layer (Oreja et al. 2025). While surface seed depletion most likely resulted from higher germination rates supported by favorable conditions, light, oxygen, temperature, moisture, and thinner seed coats (Padonou et al. 2022), higher seed density at >5-10 cm by 8 WAS suggests downward movement caused by factors like rainfall, soil cracking, or bioturbation (Carvalho et al. 2019). According to these findings, even though the seed bank initially gathers close to the surface, environmental factors can gradually disperse seeds to deeper layers, underscoring the necessity of weed control plans that also consider subterranean layers deeper than 10 cm.

Table 2. The average number of seed banks at various soil depths

Treatment	Number of seed bank / 63.59 cm² of soil seed bank							
	Seedling age/seed bank (WAS)							
	2	SD	4	SD	6	SD	8	%
0-5 cm	33.75 a	±23.13	38.75 a	±22.77	40.00 a	±22.77	48.75 (41.14) a	±26.58
>5-10 cm	24.25 ab	±18.15	31.00 a	±16.31	35.50 a	±15.33	51.50 (43.45) a	±17.94
>10-15 cm	8.75 bc	±8.30	10.25 b	±9.95	11.25 b	±13.79	12.50 (10.55) b	±15.46
>15-20 cm	4.75 c	±1.71	5.25 b	±1.89	5.50 b	±1.91	5.75 (4.85) b	±2.36
P. Value	0.074		0.015		0.017		0.009	

Description: Numbers followed by the same letter at the same age are not significantly different based on the DMRT test at α 0.05. Numbers outside brackets represent the number of sprouts, and numbers inside brackets represent the percentage of sprouts

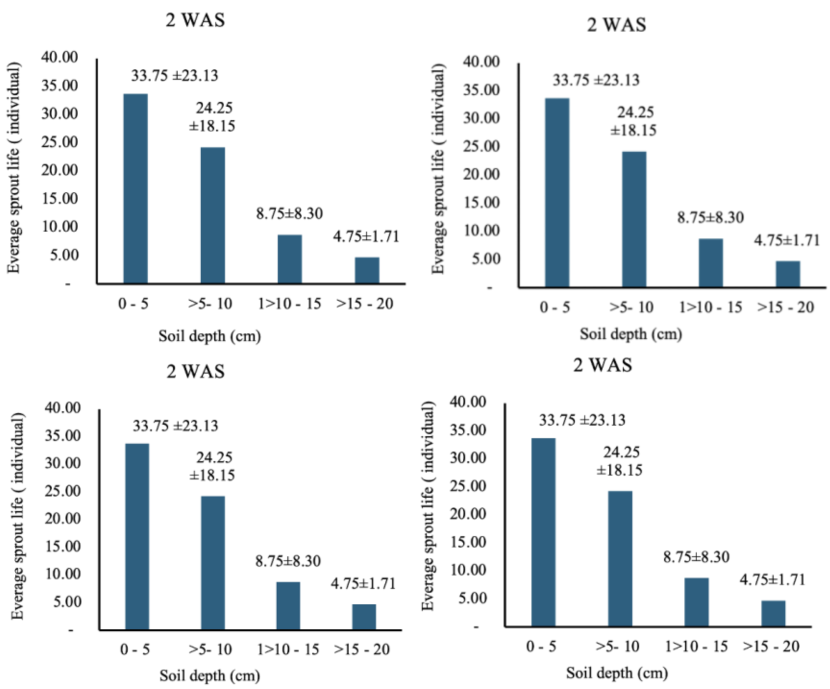

Figure 2. Histogram distribution of seed numbers at depth intervals

The most significant weed seed bank density was consistently found at the 0-5 cm depth at 2, 4, and 6 WAS, as shown in Figure 2. This is probably because seeds generated on the surface concentrate there. However, the maximum density moved to a depth of >5-10 cm by 8 WAS. According to studies by Amini et al. (2024), environmental factors such as rainfall, runoff, soil cracking, and soil fauna can transfer seeds from the surface to deeper layers. Furthermore, due to favorable light, moisture, and temperature, seeds on the surface typically germinate more quickly, gradually decreasing in number compared to those in deeper layers.

Both biotic and abiotic factors, such as crop type, climate, soil disturbance, and tillage, influence the vertical distribution of the seed bank. It has been demonstrated that conservation agricultural techniques, like residue retention and strip tillage, decrease seed bank density and variety by reducing soil disturbance and lowering germination conditions (Kumar et al. 2024). The field in this study was heavily tilled until September 2020, at which point it was left tillage-free for 2.3 years. In line with research showing that usually tilled soils disperse seeds down to 12-16 cm, while undisturbed soils concentrate seeds at 0-5 cm, such vigorous tillage can spread seeds deeper into the soil (Mishra et al. 2022). When left undisturbed for years, seeds that are 5-10 cm in length tend to stay dormant (Oreja et al. 2025).

The graph indicates that the density of weed seed banks decreases beyond a depth of 10 cm, most likely due to insufficient precipitation-induced fracture and minimal soil disturbance, which limit seed transportation. Nur-e-Janat et al. (2019) found that seed variety and quantity peaked at depths of 0-5 cm and decreased with increasing depth. This implies that since germination declines with burial and less ploughing, deeper layers contain fewer, less varied seeds. Similarly, Tóth et al. (2025) noted a decline in emergence and richness in deeper wet grassland soils, where seeds remain dormant under adverse conditions.

Weed control and soil management are reflected in this vertical distribution, which is strongest at the surface and decreases with depth (Carvalho et al. 2019). This pattern is also influenced by tillage: no-till leaves seeds at the surface, increasing germination cues, but conventional tillage buries seeds deeper, extending dormancy and decreasing emergence (Oreja et al. 2025).

In this study, seeds remained concentrated in the upper strata due to limited mechanization and minimal disturbance over the previous two to three years, a pattern consistent with those observed in tropical perennial crop systems (Ehrampoosh et al. 2025). Seasonal shifts can be caused by physical processes such as soil cracking, erosion, and bioturbation, which can redistribute seeds between strata (Carvalho et al. 2019). High rainfall encourages surface erosion and sedimentation in tropical perennial systems, such as oil palm, which causes seeds to be shifted to deeper strata or new locations (Amini et al. 2024). Seed dormancy plays a crucial role in the vertical distribution of the seed bank. Seeds buried deeper tend to remain dormant due to limited oxygen, stable temperatures, and absence of light (Saatkamp et al. 2018). Despite their dormancy, many remain viable for years and germinate when exposed to favorable conditions such as light, moisture, and temperature (Ali et al. 2021). This delayed emergence supports the persistence of weed populations and highlights the need for surface-level seed bank management.

In these systems, variety and density decrease with depth, and seed reserves are concentrated in the top 10 cm (Zhang et al. 2025). This illustrates the tactics used by weeds to persist in upper strata as well as the impact of sporadic disturbances (Zamljen et al. 2024). Surface-level weed seed bank management strategies—such as mulching, use of cover crops, and minimizing soil disturbance—may contribute to seed depletion by increasing exposure to environmental stresses and seed predators. However, the effectiveness of these approaches requires further field validation in tropical perennial cropping systems (Ehrampoosh et al. 2025).

Rumex seeds, for example, remained highly viable after being submerged in such wet conditions for 11.5 years. Weeds also produce many seeds, which accumulate at the surface and contribute to the high seed abundance at depths of 0-5 cm and >5-10 cm. To research conducted by sowing soil from different depths into sterile media. This supports the findings of Mennan and Jandstra (2017), who discovered that *Veronica hederifolia* seeds buried deeper exhibited lower germination rates than those buried at the surface, indicating variations in germination capacity between strata. For restoration and management, it is therefore essential to comprehend seed quality, viability, and reserves. Cross et al. (2020) also highlighted how greenhouse factors, including light, humidity, and temperature, affect germination.

Seed bank composition

Initial weed vegetation analysis

There are clear distinctions between aboveground weed diversity and seed bank diversity, as indicated by the preliminary vegetation analysis (Table 3). Thirty-six species (one narrow-leaved and 35 broad-leaved), totaling 355 individuals, were found in the seed bank, whereas 46 species (256 individuals) were found in the vegetation study. The 3-year oil palm plantation's high level of diversity is a result of previous seed production, weed management methods, erosion, wind, animal, human, and water dissemination. Because ex-situ conditions can break dormancy through light and warmth, promoting germination, Mesquita et al. (2015) found that floristic diversity was higher in ex-situ seed bank assessments than in situ. Magrini et al. (2019) and Ensslin et al. (2023) also noted that seed evaluation and storage in warm, light settings decrease long-term viability but lessen dormancy.

Only the initial planting of oil palm plantations typically disturbs the soil; during the three-year-old oil palm trees phase, the surface remains undisturbed for roughly three years. Seeds can access sunlight, moisture, and a temperature that is favorable for germination and growth thanks to this solid surface. By maintaining seed exposure at the surface and ensuring favorable microclimates, Zamljen et al. (2024) found that no-till systems enhance weed diversity, underscoring the significance of soil disturbance, or lack thereof, in shaping weed communities.

The most prevalent weed species, according to Table 3, was *Persicaria odorata*, which had 38 individuals overall, a density of 14.48% per 2,500 cm², and the highest Sum Dominance Ratio (SDR) of 21.01. *Mucuna bracteata* (cover crop) was the second most prevalent species, with 31 individuals, an SDR of 6.66, and a density of 12.11% per 2,500 cm². Third place went to *Rhynchosia minima*, which had 30 individuals, an SDR of 5.52, and a density of 11.72% per 2,500 cm².

There were forty broadleaf species and only six narrow-leaved species in the weed population at this location. The loose soil conditions in the immature (three-year-old oil palm trees) oil palm plantation, which encourage broadleaf development and spread, are probably the cause of this domination. The distribution and composition of seed banks are significantly influenced by the physical and chemical characteristics of the soil (Shiferaw et al. 2018). According to Nainggolan et al. (2025), broadleaf weeds, such as *Ageratum conyzoides* and *C. odorata*, frequently predominate throughout the three-year-old oil palm trees and early periods of oil palm plantations. Similar trends in tropical areas indicate that grasses and ferns are less common than broadleaf weeds, which account for more than 50% of the total weed composition (Muktamar et al. 2023).

This illustrates how weeds are divided into two groups: softer, less aggressive species and persistent, competitive ones. Similar to previous findings in open and disturbed soils, broadleaf dominance in the early phases is attributed to their reproductive methods and rapid adaptation to light and space competition. The study's vegetation research reveals that broadleaf species predominate in the weed composition of the three-year-old oil palm trees area.

According to Table 3, *P. odorata* was the most prevalent weed, with 38 individuals, a cumulative dominance ratio of 21.01, and a density of 14.48% per 2500 cm². *Rhyncosia minima* came in third place with 30 individuals (11.72% per 50 cm²; dominance ratio 5.52), followed by *M. bracteata* with 31 individuals (12.11% per 50 cm²; dominance ratio 6.66).

With 40 species, broadleaf weeds outnumbered six narrow-leaved weeds in the flora. According to Shiferaw et al. (2018), the unpredictable soil conditions of the three-year-old oil palm trees oil palm estate have an impact on the spread of weed seeds. Additionally, Olowatobi and Olorummaiye (2022) classified weeds in oil palm fields as either benign or detrimental. The vegetation analysis validated the prevalence of broadleaf weeds on the property.

Identification and number of germinated seed banks

When the sprouts were counted, growing weeds were identified. By recognizing the sprouts that appeared from the observation tubes inside the greenhouse, the number and kind of viable seeds in the soil seed bank were evaluated. The quantity of viable seeds in the soil was determined by the number of seeds that sprouted. Shiferaw et al. (2018) investigated methods for evaluating soil seed banks using seedling emergence techniques. Using this method, soil samples were placed in germination-friendly environments, and the resulting seedlings were tallied as viable seeds. This method, however, may not be able to detect viable seeds that do not sprout due to adverse conditions. The weed species and corresponding numbers in each germination tray are listed in Table 4.

Table 3. Initial weed vegetation analysis in 3-year-old immature oil palm (The plants have not yet produced any yield) fields

Type	Total	Kr (%)	NJD/ SDR
Persicaria odorata / kesum leaf**	38.00	14.84	21.01
Mucuna bracteata / beans**	31.00	12.11	6.
Rhyncosia minima / beans**	30.00	11.72	5.
Asystasia gangetica / Israeli grass**	27.00	10.55	5.69
Spermacoce / false button**	26.00	10.16	9.33
Ocimum gratissimum / basil**	10.00	3.91	2.45
macrophyllum artopurpureum / curator**	9.00	3.25	3.73
Richardia scabra /rough Mexican clover**	6.00	2.34	1.55
Mimosa pudica / princess shame**	5.00	1.95	1.49
Oplismenus hirtellus / American grass*	5.00	1.95	1.42
Lophatherum gracile / bamboo grass*	5.00	1.95	1.70
Cenchrus echinus / narrow leaf grass*	5.00	1.95	1.60
Mentha piperita / peppermint**	4.00	1.56	1.97
Desmos chinensis / red flower**	3.00	1.17	1.13
Thyponium flagelliform / rat caladium**	3.00	1.17	1.13
Salvia elegans / pineapple sage**	3.00	1.17	1.39
*Hedera helix / ivy leaf***	3.00	1.17	1.20
*Parietaria officinalis***	3.00	1.17	1.15
Oxalis barriers / ground clinching**	3.00	1.17	1.26
Arum italicum / spring flower**	3.00	1.17	1.17
*Cynodon dactylon/awatan/*Bermuda grass*	2.00	0.78	0.99
Stachytarpheta jamaicensis / horse whip**	2.00	0.78	1.01
Callopogonium / legume**	2.00	0.78	1.00
Equisetum arvense / field horsetail*	2.00	0.78	1.09
Epilobium adenocaulon / broadleaf Length**	2.00	0.78	2.51
Centella asiatica / gotu kola**	2.00	0.78	1.66
*Caliptocarpus vialis***	2.00	0.78	1.08
Vigna sp. / legume**	2.00	0.78	1.08
Chenopodium album / catassol**	1.00	0.39	0.89
Ohwia caudata / legume**	1.00	0.39	0.86
Petasites japonicus / pagan**	1.00	0.39	0.86
Poeraria phaseoloides / legume**	1.00	0.39	0.94
Stachytarpheta jamaicensis / horse whip**	1.00	0.39	0.96
Xenostegia tridentata / kangkungan**	1.00	0.39	1.15
Achyranthes aspera / Jurong**	1.00	0.39	0.93
Sida rhombifolia / sidaguri**	1.00	0.39	0.86
Centrosema virginianum / butterfly pea**	1.00	0.39	0.90
Erythrina suburban / data series**	1.00	0.39	1.94
Urena lobata / pulutan**	1.00	0.39	0.87
Vernonia amygdalina / African leaf**	1.00	0.39	0.87
Amphicarpaea bracteate / American hog peanut**	1.00	0.39	0.88
*Anthurium balaoanum***	1.00	0.39	0.87
*Micropera pallida***	1.00	0.39	0.89
Digitaria ciliaris / chicken feet grass*	1.00	0.39	0.96
Sisymbrium officinale / mustard greens**	1.00	0.39	1.11
Amaranthus reflexus / Argentine spinach**	1.00	0.39	0.92
Total	256.00	100.00	100.67
Average			

Notes: 1. *Mucuna bracteate* / legumes are not considered weeds because the Plantation plants them, 2. **broadleaf, *narrow leaves

Table 4. Weed species present in the seed bank at different soil depths

No. Sequence	Seedbank species at soil depth (individual)							
	0-5		>5 cm-10		>10-15		> 15-20	
	Type	Sum	Type	Sum	Type	Sum	Type	Sum
1	*Asystasia gangetica***	65	*Asystasia gangetica***	43	*Asystasia gangetica***	14	*Asystasia gangetica***	9
2	*Platcherium bifurcatum***	8	*Plancerium bifurcatum***	28	*Agerantum conizoides***	8	*Cyperus rotundus**	7
3	*Molugo verticiliata***	8	*Anthraxon hispidus**	9	*Cyperus rotundus**	6	*Brachiaria decumbens**	4
4	*Axonopus compressus**	7	*Agerantum conyzoides***	9	*Hexasepalum terres***	6	*Hexaphallum terres***	4
5	*Oxalis barrelierri***	7	*Euphorbia heteriophylla***	7	*Plathcerium bifurcatum***	5	*Setaria viridis**	3
6	*Melastomataceae***	5	*Phyllanthus niruri***	6	*Anthraxon hispidus**	3	*Euphorbia heteriphilla***	1
7	*Plecttranthus barbatus***	5	*Melastomataceae***	5	*Phylanthus niruri***	2	*Molugo verticiliata***	1
8	*Euphorbia heterophila***	5	*Cyperus rotundus**	3	*Papaverdubium rosentte***	1	*Plectharanthus barbatus***	1
9	*Korean ginseng***	5	*Molugo verticiliata***	2	*Korean ginseng***	1	*Penisetum purpureum**	1
10	*Spermacoce latifolia***	4	*Centaurea montana***	1	*Setaria viridis**	1	*Melastomataceae***	1
11	*Penisetum purpureum**	4	*Axonopus compressus***	1	*Hedyotis corimbosa***	1	*Phyllanthus niruri***	1
12	*Ageratum conyzoides***	4	*Cantela asiatica***	1	*Melastomataceae***	1	*Salvia divinorum***	1
13	*Leptochloa panice**	2	*Oxalis cornilaculata***	1	*Torenia fournieri***	1	*Paperomia pellucida***	1
14	*Papaverdubium rosentte***	2	*Oplismenus hirtellus**	1	*Penisetum purpureum**	1	*Calea ternifiloa***	1
15	*Boeharvia diffussa***	2	*Hedyotis diffusa***	1	*Phyllanthus niruri***	1	*Phyllanthus urinaria***	1
16	*Setaria viridis**	2	*Penisetum purpureum**	1			*Cenapdium***	1
17	*Cyperus rotundus**	2	*Papaver dubium rosenste**	1			*Anthrax on hispidus**	1
18	*Mutingja calabura***	1	*Spermacoce latifolia***	1				
19	*Cantella asiatica***	1						
20	*Phillanthus niruri***	1						
21	*Paperomin pellucida***	1						
	Total	141		121		52		41

Description: *narrow-leaved, **broadleaf

Thirty-four species and 354 individuals of weeds were identified; more weeds emerged from the seed bank than were seen in the surface vegetation, suggesting burial and dormancy. This pattern is caused by both mechanical (tillage) and natural (rain, fauna) activities that move seeds deeper, influencing germination and dormancy (Forte et al. 2018; Zamljen et al. 2024). Conventional tillage promotes emergence by exposing seeds, but no-till systems decrease surface weed densities by keeping seeds dormant at depth (Sharma et al. 2020).

While wind, water, animals, and human activity influenced seed dispersion, broadleaf weeds predominated at all depths, demonstrating their adaptation and resilience (Oreja et al. 2025). Apart from the predominance of broadleaf species, the presence of Cyperaceae in the seed bank and the dormant patterns observed warrant further examination, as these characteristics have significant implications for managing and preventing weed persistence in perennial systems.

In perennial tropical settings, the Cyperaceae exhibit significant ecological resilience, albeit at a lower abundance compared to broadleaf plants. Long-term infestations are caused by sedges such as *Cyperus* and *Fimbristylis*, which even in undisturbed soils retain viable seeds and underground propagules (Alfonzetti et al. 2023). In line with observations in tropical rice and plantation soils, their presence in deeper strata in our study indicates resistance to low oxygen and light (Benvenuti and Mazzoncini 2019). Dormancy tactics that allow weeds to withstand stress and sprout when circumstances improve are reflected in vertical seed dispersal. Due to stable microclimates and less light, dormancy increases with depth, postponing germination (Formaglio et al. 2020; Oreja et al. 2025). Management of Cyperaceae is complicated by profound dormancy and persistent seed banks in perennial settings (Jiang et al. 2024). Tropical perennial soils support deeper and longer-lasting seed banks than temperate annual systems, underscoring the need for strategies that target both surface and subsurface seeds (Zhang et al. 2025). Practical methods, especially against tenacious Cyperaceae, which may evade shallow tillage and herbicides if deeper reserves are disregarded, therefore depend on an understanding of species-specific dormancy and vertical patterns (Kumar et al. 2024).

In tropical perennial cropping systems, where seed banks are more permanent and stratified than in temperate annual systems, these findings highlight the importance of incorporating species-specific information on seed dormancy and vertical distribution into management techniques.

The possibility of buried seeds regenerating when exposed to ideal light, moisture, and temperature is confirmed by the greater number of weeds (354 individuals) that germinated from the seed bank as opposed to the initial vegetation (261 individuals) (Saatkamp et al. 2018). With seeds spread by wind, water, mechanical disturbance, animals, and people, Smith et al. (2017) demonstrated a direct correlation between initial weed populations and seed bank density (Kumar et al. 2024).

Low seed bank density and frequent disturbances are necessary for effective management in order to gradually reduce the number of emerging cohorts (Oreja et al. 205). This is especially important for upper soil layers, where germination is most likely to occur because of ideal conditions (Ali et al. 2021).

Weed vegetation shift

There is a noticeable difference in the weed vegetation when comparing Tables 3 and 4. Compared to the 256 in the field (Table 3), there were 354 weed sprouts in seedling trays (Table 4). This is probably because the stimulatory conditions—enough light, water, temperature, and humidity—improved seed bank germination. Particularly, light has a significant impact on the species composition and abundance of weeds (Marzetz et al. 2020). Higher light intensities encourage germination and change the dynamics of communities.

Additionally, the weed composition varied between the seed bank that germinated and the surface vegetation. *Persicaria odorata* dominated surface vegetation (38 individuals, SDR 21.01), with *Rhynchelytrum repens* and *A. gangetica* following closely behind. The seed bank, on the other hand, was dominated by *A. gangetica* (141 individuals), which was followed by *A. conyzoides* and *Platycerium bifurcatum*. Due to soil displacement and seed bank redistribution caused by tillage and weed control methods, the density, diversity, and emergence patterns of weeds are altered (Armengot et al. 2016). By applying selective pressure to weed communities, the use of herbicides exacerbates these changes even further.

In conclusion, according to this study, the percentage of weed seeds in the soil seed bank was highest between 0 and 10 cm in depth, accounting for approximately 84.6% of all seeds. The concentration of seeds decreased noticeably as depth increased. The mismatch between surface weeds and the potential of the seed bank was highlighted by the dominance of *A. gangetica* in all soil levels, with the maximum density at 0-5 cm and decreasing at 15-20 cm. *Persicaria odorata* dominated the surface vegetation. Broadleaf weeds dominated both surface and seed bank communities, demonstrating their adaptability in nascent oil palm ecosystems. These results suggest that the topsoil (0-10 cm), where many seeds are concentrated, should be given priority in weed control. While mulching and cover crops can inhibit weed emergence from the seed bank, shallow tillage (less than 10 cm) is advised to prevent bringing buried seeds to the surface. *Asystasia gangetica*'s use as a managed cover crop is further supported by its dominance in the seed bank and its ability to control more aggressive weeds. To minimize seed bank replenishment, herbicide treatment hold be timed to coincide with seedling flushes and concentrate on the shallow seedling emergence zone during the early growth phases. Monitoring seed banks regularly is also crucial for making timely strategy adjust, particularly to stop the emergence of invasive or resistant species. For new oil palm plantations, combining shallow tillage, timely herbicide treatment, cover crops, and monitoring provides a more focused and long-term weed control strategy.

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