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Article

Litter decomposition rates of three weed species used as cover crops in oil palm plantations: Effects of unembedded and embedded conditions

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Abstract: The low productivity of oil palm in North Sumatra, Indonesia, is due to its generally low fertility, particularly in smallholder oil palm plantations with low maintenance levels. However, the use of three common weed species found in mature oil palm plantations as cover crops can improve soil fertility by determining the rate of decomposition and nutrient release from their litter. This study aimed to investigate the decomposition and nutrient release rates of three weed species as cover crops in mature oil palm plantations under unembedded and embedded conditions. This study consisted of six treatments designed using a non-factorial randomized block design with three replications. The results showed that the decomposition and nutrient release rates of the three weed species were different. *Nephrolepis biserrata* and *Asystasia gangetica* decomposed faster and released more nutrients after 90 days of decomposition compared to *Paspalum conjugatum*. The higher nutrient content of *Nephrolepis biserrata* and *Asystasia gangetica* compared to *Paspalum conjugatum* resulted in faster decomposition and nutrient release rates. In addition, the unembedded condition also causes the decomposition and release of nutrients from the litter of the three types of weeds to be faster.

Keywords: decomposition rate; sustainable agriculture; nutrient release; weed

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1. Introduction

An important ecosystem process that regulates the cycling of carbon (C), nitrogen (N), and phosphorus (P) between plants and soil is litter decomposition. Litter decomposition and nutrient release are the most fundamental ecological processes that regulate broader nutrient cycling and plant growth (Waring, 2013; Cleveland et al., 2014). Because decomposers directly mediate plant litter decomposition, the nutrient requirements of decomposer biomass and growth efficiency ultimately determine whether organic C is assimilated into decomposer biomass or respired, and whether N and P are mineralized or immobilized (Waring, 2013).

Litter is a major component of the nutrient balance involved in regulating soil organic matter accumulation, nutrient sources and recovery, and other ecosystem services (Giweta, 2020; Gill et al., 2021; Song et al., 2023; Chen et al., 2024). At the same time, the type and amount of litter is one of the main sources of total N and organic C in soil, as well as determinants of soil physical, chemical, and biological characteristics that play an important role in maintaining soil fertility (Chakravarty et al., 2019; Zheng et al., 2021; Kaźmierczak et al., 2024). The research results of Yu et al. (2020) in wetlands; Bohara et al. (2020) in forest ecosystems; Rawat et al. (2021) in mountainous areas; Zhang et al. (2023) in near-mature *Robinia pseudoacacia* plantations; Samaniego et al. (2024) in coastal Peru and the Andean highlands, show that litter quality, environmental conditions, and decomposer communities are three important components that will affect litter decomposition.

Litter decomposition has been studied more on forest litter which only focuses on the impact of changes in the chemical properties of litter (Yan et al., 2020; Zhang et al., 2022; Akoto et al., 2022) or the soil decomposition environment (Yan et al., 2020; Hu et al., 2021), studies on to study the litter decomposition of weed species that are often found in mature oil palm plantations, such as *Asystasia gangetica* (L.) T. Anderson, *Nephrolepis biserrata*, and *Paspalum conjugatum*, each of which is a type of broadleaf weed, fern and grass that can be used as a cover crop (Asbur et al., 2018), so it is necessary to know the rate of decomposition and nutrient release of the three weed species in order to estimate how much organic matter and nutrients will be contributed to the soil when used as a cover crop.

Previous studies have only examined the rate of decomposition and nutrient release of *A. gangetica* and *N. biserrata* which are still limited to one condition, namely only placed on the soil surface (without being buried) and not immersed. Therefore, in this study, the decomposition of the litter of the three weed species was carried out under different conditions, namely unembedded and embedded. 'Berg and McClaugherty (2020); Yan et al., (2020) reported that litter decomposition is controlled by several factors, including litter nutrient content, decomposition environment, composition, and decomposer activity'. Environmental conditions will greatly affect the microenvironment of litter, such as temperature, humidity, nutrient content, and soil pH (Fernández-Alonso et al., 2022; Liu et al., 2021) which will ultimately affect the composition of the decomposer community and the carbon source preferences of decomposers (Duan et al., 2022; Yang et al., 2021), so that indirectly it will also affect the rate of decomposition and release of litter nutrients (Fu et al., 2021; Fernandez-Alonso et al., 2022; Xu et al., 2022).

Based on this, this study aimed to investigate the rate of decomposition and nutrient release of litter of three weed species (*A. gangetica*, *N. biserrata*, and *P. conjugatum*) as cover crops in mature oil palm plantations under unembedded and embedded conditions.

2. Materials and Methods

2.1. Study Site

The study was conducted among rows of 15-year-old oil palm plants at the smallholder oil palm plantation in Naga Rejo Village, North Sumatra, Indonesia (3º29′22″ N-98º52′02″ E) with an annual rainfall of 1883 mm and an average annual temperature of 30.35 °C. The soil type is red-yellow podzolic according to the Dudol-Soepraptohardjo soil classification system (1957-1951), is a soil that has undergone advanced weathering with a red to yellow color and clear horizon development. This soil is also known as Acrisol in the FAO classification and Ultisol in the USDA Taxonomy.

2.2. Design

The litter decomposition experiment was arranged in six experimental plots between rows of oil palm plants representing six treatments of weed species and immersion replicated three times. The six treatments consisted of broadleaf weed litter (*Asystasia gangetica* L. (T.) Anderson) unembedded (W1); fern weed litter (*Nephrolepis biserrata*) unembedded (W2); grassy weed litter (*Paspalum conjugatum*) unembedded (W3); *A. gangetica* litter embedded (W4); *N. biserrata* litter embedded (W5); and *P. conjugatum* litter embedded (W6). The research design used a Randomized Complete Block Design.

2.3. Litter Biomass Preparation

The litter used was the weed species *A. gangetica*, *N. biserrata*, and *P. conjugatum* obtained from the research location with each litter sample weighing 150 g, consisting of all parts of the plant, namely leaves, branches, stems, and roots. Before being dried, all plants were washed to free them from soil. After that, the litter was dried and placed in a 15 cm x 20 cm litter bag made of nylon netting with a mesh size of 1 mm. For one plot, 3 litter bags were needed so that the litter needed for each treatment was: 3 litter bags per treatment x 3 replications x 150 g per litter bag = 1350 g per each litter.

Each decomposition treatment had three replications. Each replication had six treatments (experimental plots), and each experimental plot had three litter bags so that there were 54 litter bags (3 replications x 6 treatments x 3 litter bags).

2.4. Litter Bag Placement

Each litter bag was placed according to the treatment, namely: (1) litter bag embedded treatment: the litter bag was embedded to a depth of 10 cm then covered with soil; (2) litter bag treatment unembedded: the litter bag was placed on the surface of the ground then bamboo was placed on both sides to tie the litter bag so that it would not fly or be carried away by water; (3) the place where the litter bag was placed was made into a 70 cm x 20 cm plot with a distance between litter bags of 20 cm. The distance between replications was 50 cm, the distance between plots was 30 cm.

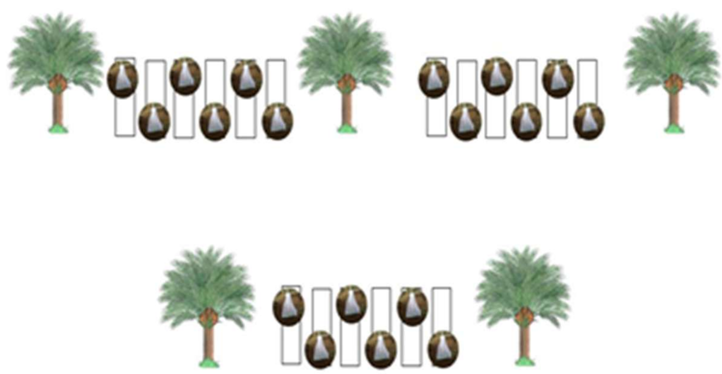


Figure 1. Litter bag placement chart at the research location

2.5. Litter Sampling and Analysis

Litter bags from each treatment were sampled three times for laboratory analysis after 30, 60, and 90 days since placement. Before analyzing the nutrient content, the litter weight was first weighed, then the litter was carefully cleaned and oven-dried at 80 °C for 48 hours, then the C (%) and N (%) content of the litter was analyzed using the H_2SO_4–$K_2Cr_2O_7$ oxidation method (Liu et al., 1996) and the Kjeldahl method (Grimshaw, 1958), while the P (%) content of the litter using a wet destruction method of 18% perchloric acid followed by the Scheel method (Purcell and King, 1996), and Potassium (K%) using a wet destruction method of 18% perchloric acid followed by the reading activity using AAS spectra 40 (Jones and Case, 1990).

2.6. Calculations and Statistical Analysis

Litter Weight (g). Litter weight was weighed at the beginning of the treatment and at 30, 60, and 90 days after the litter was placed in the experimental plot. At the beginning of the treatment, the litter biomass weight measured was the litter biomass weight in an air-dry state, while the litter biomass weight measurements at 30, 60, and 90 days after treatment were measurements of the biomass weight of the biomass after 30, 60, and 90 days in the field or after decomposition.

Biomass Decomposition Percentage (%). The percentage of biomass decomposition was obtained using the equation (Wang et al., 2018):

$$Y = \frac{W0 - Wt}{Wt} \times 100\%, \quad (1)$$

where: Y = percentage of biomass that undergoes decomposition (%); W0 = initial dry weight of biomass (g); Wt = dry weight of biomass after observation time t (g); t = observation time (days).

Decomposition Rate (g/day). The decomposition rate is calculated from the reduction in the weight of the composed biomass in one unit of time using the equation (Ribiero et al., 2002):

$$R = \frac{W0 - Wt}{t}, \quad (2)$$

where: R = decomposition rate (g/day); W0 = initial biomass dry weight (g); Wt = biomass dry weight after observation time t (g); t = observation time (days).

Changes in C and N, P, K Content of Litter (%). The relative changes in litter C and N, P, K content (RC and RN, RP, RK) during a certain period from 0 to t were calculated using Equation (Wang et al., 2020):

$$RC = \frac{(Xt \times Ct)}{(X0 \times C0)} \times 100\%, \quad (3)$$

$$RN = \frac{(Xt \times Nt)}{(X0 \times N0)} \times 100\%, \quad (4)$$

$$RP = \frac{(Xt \times Pt)}{(X0 \times P0)} \times 100\%, \quad (5)$$

$$RK = \frac{(Xt \times Kt)}{(X0 \times K0)} \times 100\%, \quad (6)$$

where: X0, C0, D0, P0, K0, Xt, Ct, Bt, Pt, and Kt respectively represent the dry weight, C, N, P, and K content of litter at the initial time and a certain time t.

One-way ANOVA was used to compare the decomposition rate and quality indicators of each type of litter (litter of three weed species in buried and unburied conditions) and continued with the LSD test at a significance level of $P \leq 0.05$ (Gomez and Gomez, 1984) if the treatments given were significantly different.

3. Results

3.1. Litter Condition

In this study, three weed species were used as cover crops in a productive oil palm plantation and tests were carried out on the decomposition of their litter under unembedded and embedded conditions.

The litter of three weed species experienced significant decomposition during the decomposition period of 30, 60, and 90 days. The litter species that decomposed the most during the decomposition period was *N. biserrata* both unembedded and embedded (W2 and W5), which were respectively 66.56-66.66%, 87.13-87.95%, 94.02-94.66% in unembedded (W2) and 65.59-66.99%, 86.70-88.52%, 88.75-91.55% in embedded (W5). The litter with the least litter decomposition was *P. conjugatum* both unembedded and embedded (W3 and W6), namely 45.98-46.80%, 66.78-69.38%, 78.96-80.145 in unembedded (W3) and 33.19-33.93%, 42.69-43.45%, 52.08-53.78% in embedded. When viewed from the embedded conditions, the unembedded litter decomposed more for the three weed species compared to the embedded litter (Table 1).

The litter of the three species in the unembedded and embedded conditions also showed significant differences in decomposition rates (Table 2). The litter species with the fastest decomposition rate was *N. biserrata* both unembedded and embedded (W2 and W5), which were respectively 3.32-3.34 g/day, 2.18-2.20 g/day, 1.56-1.58 g/day in unembedded (W2), and 3.27-3.35 g/day, 2.17-2.21 g/day, 1.48-1.52 g/day in embedded (W5) followed by *A. gangetica* litter both unembedded and embedded (W1 and W4), which were respectively 2.96-3.00 g/day, 1.99-2.05 g/day, 1.50-1.54 g/day in unembedded (W1) and 2.98-3.00 g/day, 1.60-1.62 g/day, 1.43-1.45 g/day in embedded (W4). The lowest decomposition rate was *P. conjugatum* litter both unembedded and embedded (W3 and W6), which were respectively 2.30-2.34 g/day, 1.67-1.73 g/day, 1.32-1.34 g/day, and 1.65-1.67 g/day in unembedded (W3), 1.07-1.09 g/day, 0.87-0.89 g/day in embedded (W6) (Table 2).

Table 1. Percentage of litter decomposition of three weed species (%) under unembedded and embedded conditions during decomposition periods of 30, 60, and 90 days.

Treatments	Decomposition periods (days)		
	30	60	90
W1	59.67 ± 0.33[b]	80.69 ± 1.01[b]	91.19 ± 0.32[b]
W2	66.61 ± 0.05[a]	87.54 ± 0.41[a]	94.34 ± 0.32[a]
W3	46.39 ± 0.41[c]	68.08 ± 1.30[c]	79.55 ± 0.69[d]
W4	59.91 ± 0.08[b]	64.35 ± 0.41[d]	86.27 ± 0.39[c]
W5	66.29 ± 0.70[a]	87.61 ± 0.91[a]	90.15 ± 1.40[b]
W6	33.26 ± 0.07[d]	43.07 ± 0.38[e]	52.93 ± 0.85[e]

Mean ± standard deviation; W1: *A. gangetica* litter unembedded; W2: *N. biserrata* litter unembedded; W3: *P. conjugatum* litter unembedded; W4: *A. gangetica* litter embedded; W5: *N. biserrata* litter embedded; W6: *P. conjugatum* litter embedded; Small letters in the upper index of the mean values mean significant differences between treatments.

Table 2. Decomposition rate of litter of three weed species (g/day) under unembedded and embedded conditions during decomposition periods of 30, 60, and 90 days.

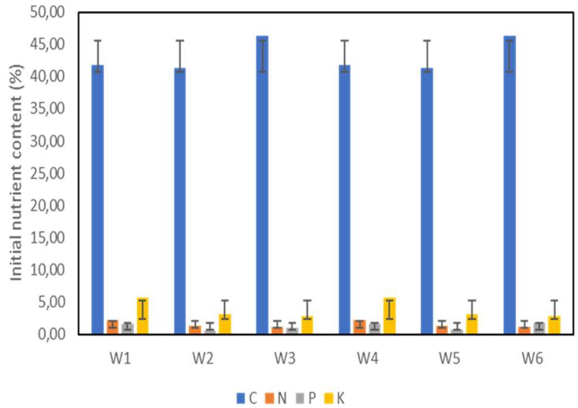
Treatments	Decomposition periods (days)		
	30	60	90
W1	2.98 ± 0.02[b]	2.02 ± 0.03[b]	1.52 ± 0.02[b]
W2	3.33 ± 0.01[a]	2.19 ± 0.01[a]	1.57 ± 0.01[a]
W3	2.32 ± 0.02[c]	1.70 ± 0.03[c]	1.33 ± 0.01[d]
W4	2.99 ± 0.01[b]	1.61 ± 0.01[d]	1.44 ± 0.01[c]
W5	3.31 ± 0.04[a]	2.19 ± 0.02[a]	1.50 ± 0.02[b]
W6	1.66 ± 0.01[d]	1.08 ± 0.01[e]	0.88 ± 0.01[e]

Mean ± standard deviation; W1: *A. gangetica* litter unembedded; W2: *N. biserrata* litter unembedded; W3: *P. conjugatum* litter unembedded; W4: *A. gangetica* litter embedded; W5: *N. biserrata* litter embedded; W6: *P. conjugatum* litter embedded; Small letters in the upper index of the mean values mean significant differences between treatments.

3.2. C content, and N, P, K Nutrients in Litter

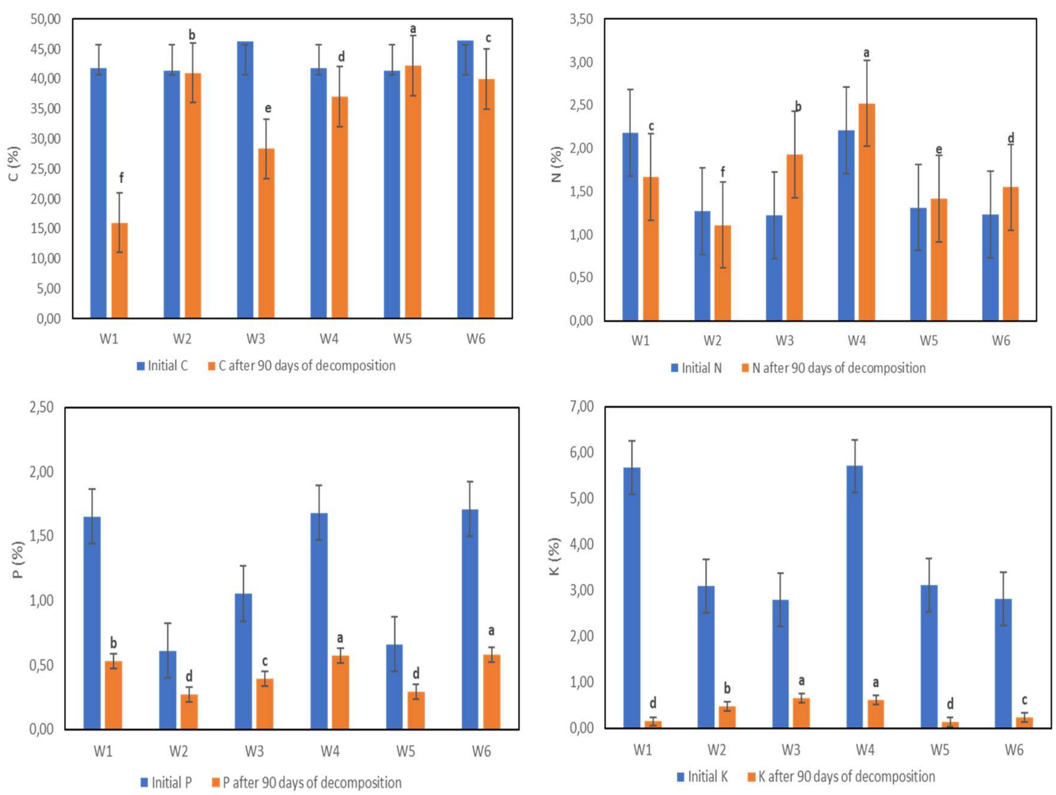
The litters of three weed species had different initial C, N, P, and K contents (Figure 2). P. *conjugatum* litters (46.29% on W3, and 46.37% on W6) had higher initial organic C contents compared to *A. gangetica* (41.81% on W1, and 41.82% on W4) and *N. biserrata* (41.36% on W2, and 41.35% on W5) litters, while *A. gangetica* litters (W1 and W4) had higher N, P, and K contents, namely 2.18%, 1.65%, 5.67% respectively in unembedded (W1), and 2.21%, 1.68%, 5.70% in embedded (W4) compared to *N. biserrata* litter (W2 and W5), namely 1.27%, 0.61%, 3.09% respectively in unembedded (W2), 1.31%, 0.66%, 3.12% in embedded (W5), and *P. conjugatum* (W3 and W6), namely 1.22%, 1.05%, 2.78% respectively in unembedded (W3), and 1.23%, 1.71%, 2.81% in embedded (W6). *N. biserrata* litter was characterized by low C, N, P, and K contents (Figure 2).

The C, N, P, K content of the litter of three weed species after 90 days of decomposition changed and differed significantly for each treatment (Figure 3). The litter of *N. biserrata* that was embedded (W5) and unembedded (W2) still had a high C content, namely 42.22% in W5 and 41.00% in W2 respectively, followed by embedded *P. conjugatum* litter (W6), namely 39.99%, and embedded *A. gangetica* litter (W4), namely 37.08%, while the lowest litter C content was found in unembedded *A. gangetica* litter (W1), namely 16.02% (Figure 3).



W1: *A. gangetica* litter unembedded; W2: *N. biserrata* litter unembedded; W3: *P. conjugatum* litter unembedded; W4: *A. gangetica* litter embedded; W5: *N. biserrata* litter embedded; W6: *P. conjugatum* litter embedded.

Figure 2. Initial litter C, N, P, and K content



W1: *A. gangetica* litter unembedded; W2: *N. biserrata* litter unembedded; W3: *P. conjugatum* litter unembedded; W4: *A. gangetica* litter embedded; W5: *N. biserrata* litter embedded; W6: *P. conjugatum* litter embedded; Small letters above the bar graph indicate significant differences between treatments.

Figure 3. C, N, P, and K content of initial litter and 90 days after decomposition

Litter N content was significantly different between weed species treatments under unembedded and embedded conditions (Figure 3). *A. gangetica* embedded litter (W4) had the highest N content, namely

2.52%, which was significantly different from the N content of other litters. Unembedded *N. biserrata* litter (W2) had the lowest N content, namely 1.11%. The P and K contents of the litter of the three weed species under embedded and unembedded conditions were also significantly different (Figure 3). The highest litter P content was found in *P. conjugatum* and *A. gangetica* embedded litters (W6 and W4), which were 0.58% in W6 and 0.57% in W4, respectively, while N. biserrata litter, both unembedded and embedded (W2 and W5) had the lowest P content, which were 0.27% in W2 and 0.29% in W5, respectively. The highest litter K content was found in unembedded *P. conjugatum* litter (W3), which was 0.65% and embedded *A. gangetica* litter (W4), which was 0.61%, while the lowest litter K content was found in unembedded *A. gangetica* litter (W1), which was 0.14%, and embedded *N. biserrata* litter (W5), which was 0.13%.

3.3. Litter Nutrient Release

Table 3. Release of C and nutrients N, P, K from the litter of three weed species (%) under buried and unburied conditions during the decomposition period of 30, 60, and 90 days

Treatments	Decomposition periods (days)		
	30	60	90
		Release C (%)	
W1	95.31±0.08^{a}	93.40±0.61^{d}	98.98±0.16^{a}
W2	93.80±0.14^{c}	96.14±0.04^{b}	98.32±0.09^{b}
W3	92.75±0.20^{d}	98.53±0.06^{a}	96.24±0.21^{d}
W4	94.72±0.04^{b}	94.22±0.17^{c}	96.35±0.12^{d}
W5	93.95±0.13^{c}	98.53±0.06^{a}	96.98±0.41^{c}
W6	92.77±0.05^{d}	88.47±0.38^{e}	87.82±0.18^{e}
		Release N (%)	
W1	85.35±0.30^{a}	96.33±0.22^{cd}	97.98±0.25^{a}
W2	84.61±0.67^{a}	97.78±0.12^{a}	98.52±0.14^{a}
W3	85.76±0.64^{a}	96.88±0.25^{b}	90.30±0.30^{d}
W4	85.48±0.64^{a}	96.13±0.30^{d}	95.29±0.33^{c}
W5	84.80±0.32^{a}	96.72±0.25^{bc}	96.82±0.47^{b}
W6	74.99±1.31^{b}	92.09±0.36^{e}	82.24±0.58^{e}
		Release P (%)	
W1	72.92±0.92^{d}	96.57±0.37^{c}	99.15±0.14^{a}
W2	87.47±0.67^{b}	94.25±0.18^{d}	99.25±0.07^{a}
W3	91.27±2.05^{a}	94.62±0.47^{d}	97.73±0.15^{c}
W4	81.17±0.26^{c}	97.65±0.16^{a}	98.60±0.08^{b}
W5	91.69±1.02^{a}	96.93±0.62^{b}	98.70±0.22^{b}
W6	90.01±0.47^{a}	97.37±0.35^{ab}	95.21±0.34^{d}
		Release K (%)	
W1	97.48±0.05^{b}	99.81±0.01^{a}	99.93±0.01^{a}
W2	98.44±0.06^{a}	99.35±0.03^{b}	99.74±0.01^{b}
W3	98.55±0.29^{a}	98.72±0.16^{c}	98.57±0.15^{e}
W4	98.51±0.07^{a}	99.72±0.10^{a}	99.56±0.03^{c}
W5	98.22±0.08^{a}	99.33±0.03^{b}	99.88±0.04a
W6	95.72±0.75^{c}	99.51±0.43^{ab}	98.84±0.09^{d}

Mean ± standard deviation; W1: *A. gangetica* litter unembedded; W2: *N. biserrata* litter unembedded; W3: *P. conjugatum* litter unembedded; W4: *A. gangetica* litter embedded; W5*: N. biserrata* litter embedded; W6: *P. conjugatum* litter embedded; Small letters in the upper index of the mean values mean significant differences between treatments.

During decomposition, litter will release carbon (C) and nutrients N, P, K contained in the litter tissue. The release of C, and nutrients N, P, K increased from the 30-day to 60-day decomposition period, and decreased in the 90-day decomposition period (Table 3).

The release of C, and nutrients N, P, K of the litter of three weed species in unembedded and embedded conditions showed significant differences after 30, 60, and 90 days of decomposition. The highest C release was found in *A. gangetica* litter unembedded (W1), which were 95.23-95.39%, 92.79-94.01%, and 98.82-99.14%, respectively, followed by *N. biserrata* litter unembedded (W2), which were 93.66-93.94%, 96.10-96.18%, and 98.23-98.41%, respectively, while the lowest C release was in embedded *P. conjugatum* litter (W6), which were 92.72-92.82%, 88.09-8885%, and 87.64-88.00%, respectively. The C release for the three litter species showed that the unembedded condition resulted in higher C release than the embedded condition (Table 3).

The release of N, P, and K nutrients differed significantly between treatments. The highest release of N, P, and K nutrients was found in *A. gangetica* litter unembedded (W1), which were respectively 85.05-85.65%, 72.00-73.84%, 97.43-97.53% after 30 days of decomposition, 96.11-96.55%, 96.20-9694%, 99.80-99.82% after 60 days of decomposition, and 97.73-98.23%, 99.01-99.29%, 99.92-99.94% after 90 days of decomposition. The litter of *N. biserrata* unembedded (W2) also showed the highest release of N, P, and K nutrients, namely 83.94-85.28%, 86.80-88.14%, 98.38-98.50% after 30 days of decomposition, 97.66-97.90%, 94.07-94.43%, 99.32-99.38% after 60 days of decomposition, and 98.38-98.66%, 99.18-99.32%, 99.73-99.75% after 90 days of decomposition. The litter of *P. conjugatum* embedded (W6) showed the lowest release of N, P, K nutrients, which were respectively 73.68-76.30%, 89.54-90.48%, 95.66-95.78% after 30 days of decomposition, 91.73-92.45%, 97.02-97.72%, 99.08-99.94% after 60 days of decomposition, and 81.66-82.82%, 94.87-95.55%, 98.75-98.93% after 90 days of decomposition. Similar to the release of C, the release of N, P, K nutrients in the three litter species also showed the highest release of N, P, K nutrients in the unembedded condition compared to embedded (Table 3).

4. Discussion

4.1. Litter Condition

The nature of the soil in smallholder oil palm plantations is generally infertile and tends to degrade due to improper management, such as intensive weed control using herbicides. In fact, weeds that grow under oil palm stands can be used as ground cover and can improve the chemical properties of the soil through the decomposition of its litter. 'Kaźmierczak et al. (2024) stated that soil properties are greatly influenced by the quality of litter and its decomposition rate'. This has been demonstrated in previous studies that confirmed the role of the composition of decomposed litter nutrient content in shaping soil properties (Błońska et al., 2021; Chen et al., 2021).

The litter decomposition rate of three weed species under unembedded and embedded conditions was significantly different during the decomposition period of 30, 60, and 90 days. During the decomposition period, *N. biserrata* and *A. gangetica* litters decomposed faster than *P. conjugatum* litters. *P. conjugatum* litter is a grass litter with a higher lignin content (Nurhayu and Saenab, 2019) compared to *A. gangetica* litters (Nulfiana, 2016) and *N. biserrata* (Oyawaluja et al., 2024). The presence of lignin in litter will limit its decomposition rate (Guo et al., 2021; Hall et al., 2020), while litter with low lignin content, the litter decomposition rate will be higher (Erdenebileg et al., 2023). An essential organic component of plant litter, lignin is typically thought to be very limiting to the rate at which litter decomposes (Kögel-Knabner, 2017).

In addition, the composition of the nutrient content of *N. biserrata* and *A. gangetica* which is higher than that of *P. conjugatum* also causes the quality of the litter to be different. Different litter qualities will regulate different enzyme activities and ultimately affect the rate of litter decomposition (Long et al., 2024; Huang et al., 2024; Li et al., 2024). Several studies have shown that litter quality plays a much stronger role in determining the rate of litter decomposition than microbial activity (Liao et al., 2022). In their research of forest ecosystems, Kohl et al. (2023) also discovered that the rate and direction of litter decomposition were significantly and variably impacted by naturally occurring fluctuations in litter nutrient concentrations.

The structure and chemical properties of plants not only differ between species, but also between the same plant organs, such as roots, stems, and leaves, there are differences (Freschet et al., 2012), and leaf litter generally decomposes faster than stem and fine root litter (Sun et al., 2018; Guo et al., 2021). In addition, decomposition is also significantly affected by the combination of C and N. Generally, higher N content or lower C/N ratio indicates a higher decomposition rate (Xing et al., 2024). This also causes *P. conjugatum* litter to take longer to decompose than *A. gangetica* and *N. biserrata* litter because the N content of *P. conjugatum* litter is lower than the N content of *A. gangetica* and *N. biserrata* litter (Figure 2).

The litter decomposition rate of *A. gangetica*, *N. biserrata*, and *P. conjugatum* was faster in the unembedded condition than in the embedded condition (Tables 1 and 2). This is because litter decomposition is influenced by soil temperature and moisture (Magh et al., 2024). In the unembedded condition, litter still receives solar radiation which can help accelerate litter photodegradation (Xing et al., 2024), and will modulate the efficiency of soil fauna that act as decomposers to decompose litter, thus having a significant effect on the rate of litter decomposition (Su et al., 2023; Li et al., 2024).

4.2. C content, and N, P, K nutrients in litter

The C and nutrient content of N, P, K of the three litter species changed after 90 days of decomposition. This is because during the decomposition process, litter will change over time due to the main processes: (1) nutrient leaching through the transfer of soluble materials carried to lower soil layers for further processing by decomposers; b) fragmentation occurs when large pieces of litter are physically broken down into smaller pieces; and c) chemical changes occur when decomposers recognize molecules or only use part of the molecules during biomass production (Liira et al. 2007).

The chemical composition of litter changes during decomposition as structural and soluble compounds are degraded (Aragão et al., 2009), where soil fauna and microorganisms play an important role during the decomposition process. Soluble nutrients will first be leached and then mineralized or immobilized according to the demand of the decomposer community (Krishna and Mohan 2007). The C content in litter will decrease with decomposition time, but the loss of C in litter is determined by the growth rate and efficiency of decomposers because organic C in litter is the main energy source for decomposers (Giebelmann et al., 2013). In addition, litter quality, nutrient availability, temperature, and water availability are also major factors that determine the growth rate and efficiency of decomposers.

Nitrogen is a good indicator of decomposition rate (Du et al., 2020). Litter N content increased after 90 days of decomposition in all three buried litter species. This proves that N plays a major role in influencing the rate of litter decomposition, where litter with high N content tends to decompose faster because N is an important nutrient to increase microbial activity that accelerates the decomposition of organic matter (Magh et al., 2024). In this study, it was seen that N accumulated more in litter after 90 days of decomposition which is consistent with the findings of Spohn and Berg (2023); Magh et al. (2024). Similar observations have been reported by 'Sagala (2018), where atmospheric N fixation and its immobilization by decomposers caused a temporary increase in N concentration in decomposed litter'. This is because during the litter decomposition process, the organic C content decreases which may affect the percentage increase in N in the litter (Magh et al., 2024).

Increased N content in all three litter species occurred in the buried litter. Most likely, this increase in litter N content originated from the nutrient-rich mineral soil or litter layer, and was transported by fungi, mobile prokaryotes, soil microfauna, and insects (Filipiak, 2018), or through N_2 fixation (Rinne et al., 2017). Much of this was also due to fungal colonization of the litter, i.e., biomass movement, and aging of the N-rich fungal biomass in the colonized litter (Osono and Takeda, 2001). In addition, N transport via the formed fungal mycelium and the release of N-rich exoenzymes could contribute to the increase in N in the litter (Sinsabaugh et al., 2002). By colonizing litter massively and supplementing it with N-rich necromass, fungi create a pool of organic matter that is stoichiometrically close to their own biomass compared to plant litter (Manzoni et al., 2021; Spohn and Berg, 2023).

The P content of *P. conjugatum* litter after 90 days of decomposition was higher than that of *A. gangetica* and *N. biserrata* litter, both without immersion and immersion. This is because *P. conjugatum* litter, which is grass litter, contains higher lignin than *A. gangetica* and *N. biserrata* litter (Nurhayu and Saenab, 2019; Nulfiana, 2016; Pagarra et al., 2014). The lignin content in litter tends to be resistant or slower to decompose compared to other compounds found in litter, where lignin content also contains N and P elements (Berg and McClaugherty, 2020), so litter with higher lignin content tends to have higher P content in its litter. The same results were also reported by Magh et al. (2024) that pine litter with high lignin content produces high P content during the decomposition process.

In contrast to the C, N, and P content, the K content of the three types of litter was very low in the litter after 90 days of decomposition in unembedded and embedded conditions because K is less strongly retained in the litter (Berg and McClaugherty, 2020) and is quickly washed out of the decomposed plant litter (Osono and Takeda, 2004).

4.3. Litter Nutrient Release

The release of C, and N, P, K nutrients increased from the 30-day to 60-day decomposition period, and decreased in the 90-day decomposition period. In line with the research results of 'Rogers (2002); Asbur and Purwaningrum (2018) which also showed an increase in the release pattern of C, and N, P, K nutrients during the decomposition period'. The release of C and N, P, K nutrients from litter plays an important role in the addition of organic matter and soil nutrients. Litter is the main source of organic matter for the soil, and litter decomposition positively affects the physical and chemical characteristics of the soil (Joly et al., 2023; Pereira et al., 2023; Kaźmierczak et al. 2024).

Litter of *A. gangetica* and *N. biserrata*, both in unembedded and embedded conditions, released more C and nutrients N, P, K compared to litter of *P. conjugatum*. This is also related to the decomposition rate of the three litter species, where litter with a faster decomposition rate will also release more C and nutrients N, P, K which are important for soil fertility. In line with several research results reported by Hu et al. (2022); Zhao and Huang, (2023); Kazmierczak et al. (2024).

K is a nutrient with the largest decrease in concentration and release of nutrients compared to C, N and P. This is in line with the research results of 'Asbur and Purwaningrum (2018) which showed that the release of K nutrients was the fastest compared to C, N, and P nutrients. This may be due to the high mobility and solubility of K in water (Rogers, 2002; Nugroho et al., 2025)

The release of C, N, P, and K nutrients was generally faster in unembedded conditions than in embedded conditions, both in *A. gangetica*, *N. biserrata*, and *P. conjugatum* litters (Table 3). The release of litter nutrients is greatly influenced by abiotic factors such as temperature, humidity, litter quality, and biotic factors such as enzyme activity, microbial biomass, and the interaction of the two factors (Prieto et al., 2019; Malik et al., 2020). Among these factors, temperature is considered the main factor controlling litter decomposition, due to its direct effect on microbial activity and its indirect effect on litter nutrients by inducing morphological and physiological changes in plants (Suseela and Tharayil, 2018). The results of this study are in line with the results of studies by Bravo-Oviedo et al. (2017); Predick et al. (2018); Asbur and Purwaningrum (2018); Liu et al. (2022). According to Baker and Allison (2015), higher levels of solar radiation in unembedded conditions compared to embedded conditions can increase the rate of litter decomposition by microbes, thereby accelerating the decrease in litter nutrient concentrations and increasing litter re-release. This is because at higher levels of solar radiation, high temperatures will increase the activity of microorganisms (Chapin III et al., 2002).

5. Conclusions

Environmental conditions and nutrient content of litter are the main determinants of the rate of decomposition and release of C, and dissolved nutrients N, P, K during litter decomposition. It can be seen from the results of the study that the decomposition rates of *N. biserrata* and *A. gangetica*, which have higher nutrient content compared to *P. conjugatum* also showed a faster decomposition rate. The decomposition of litter of the three weed species was also faster in conditions unembedded compared to embedded.

The use of weeds such as *N. biserrata*, *A. gangetica*, and *P. conjugatum* as cover crops in mature oil palm plantations better results than controlling them using herbicides because they can return organic matter through their organic C content, and N, P, K nutrients to the soil which can play a role in improving the chemical properties of the soil in oil palm plantations.

Future studies should focus on how various environmental factors, including temperature, soil moisture, and sunlight, interact with soil microbial activity to influence the breakdown of weed litter in oil palm plantations.

Author Contributions: For research articles with several authors, a short paragraph specifying their individual contributions must be provided. The following statements should be used "Conceptualization, Y.A. and Y.P.; methodology, Y.A.; software, M.A.; validation, M.A., A.S. and F.C.M.; formal analysis, Y.P.; investigation, F.C.M.; resources, Y.A.; data curation, M.A and A.S.; writing—original draft preparation, Y.A.; writing—review and editing, Y.A.; visualization, Y.P.; supervision, Y.A and Y.P.; project administration, M.A. and A.S.; funding acquisition, Y.A. All authors have read and agreed to the published version of the manuscript."

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