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Evaluation of the suitability of three weed species as alternative cover crops in smallholder oil palm plantations through plant spacing management

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Abstract

Smallholder oil palm plantations in Indonesia have reached 8.9 million ha, but their role is still not optimal due to low productivity caused by the lack of knowledge of smallholders regarding sustainable oil palm technical culture, such as the use of cover crops. However, it requires appropriate spacing for different species. This study aims to obtain the optimum spacing of 3 weed species planted as cover crops in smallholder oil palm plantations. The research was carried out in 2022 at the smallholder oil palm plantation Naga Rejo village, Galang, Sumatera Utara, Indonesia. The experimental treatments included weed species (*Asystasia gangetica*, *Paspalum conjugatum* and *Nephrolepis biserrata*) as the main plot and spacing (10, 20 and 30 cm) as subplots arranged in a separate plot design with 3 replications. The results showed that the % of 100% land coverage was obtained in plantings of *N. biserrata* and *A. gangetica* in 4 WAPs and 10 cm spacing in 3 WAPs independently. The highest leaf area of *N. biserrata*, *P. conjugatum* and *A. gangetica* was obtained at a spacing of 30 cm. The highest dry weight, growth rate and nutrient uptake N and K *N. biserrata* and *P. conjugatum* were obtained at a spacing of 10 cm, while *A. gangetica* at a spacing of 30 cm. This shows that the optimum spacing depends on the weed species. The optimum spacing for *A. gangetica* (broad leaf) is 30 cm, while for *P. conjugatum* (grasses) and *N. biserrata* (ferns) is 10 cm.

Keywords

land coverage; oil palm; plant spacing; weed

Introduction

Oil palm (*Elaeis guineensis* Jacq.) is one of the leading plantations in Indonesia, including in Sumatera Utara. Currently, smallholder oil palm plantations in Indonesia have reached 8.9 million ha (1) and have a strategic role not only for the Indonesian oil palm industry but also in increasing welfare and economic growth in various oil palm development areas. However, the role of oil palm plantations is still not optimal because their productivity is still low. This is due to the lack of knowledge regarding the technical culture of sustainable palm oil. The sustainability of oil palm plantations is one of the main priorities (47), listed in the ISPO (Indonesian Sustainable Palm Oil) certification system, which was established in 2009, and RSPO (Roundtable on Sustainable Palm Oil), which was established in 2004, such as plant and animal biodiversity and increasing the efficiency of resource use, as a resource that aims to ensure the provision of ecosystem services in a sustainable manner.

Planting cover crops is one way to increase biodiversity in oil palm plantations. However, one of the main obstacles to its implementation is the need to use plant species that are adapted to the shade conditions under mature oil palm stands. Generally, the use of cover crops in oil palm plantations is only done when the oil palm plants are immature by planting the *Mucuna bracteata* legume (51), but naturally *M. bracteata* will die as the oil palm ages because it is not tolerant to the shade of the oil palm canopy and will be replaced by various types of weed species such as *Asystasia gangetica*, *Paspalum conjugatum*, *Nephrolepis biserrata*, *Axonopus compressus* and *Stachytarpheta indica*. The main problem will arise because the smallholder oil palm planters will generally control these weeds using herbicides regularly to avoid weed competition with the oil palm trees in extracting water and nutrients, which results in a decrease in weed vegetation coverage. The smallholder oil palm plantation in Desa Naga Rejo, Galang, Deli Serdang has a moderate biodiversity index (H'= 1.0-1.5) based on the Shannon diversity index (2), which points to the need to implement soil conservation practices, such as planting cover crops for increase biodiversity and prevent soil erosion during the rainy season (3, 4, 48).

Studies on the use of weed species as cover crops have mostly been conducted in vineyards and olive groves. There is relatively much research on the potential of weeds as cover crops in certain environments, such as vineyards (5, 6), almond orchards (7), and olive groves (8, 9). Most types of cover crops used in vineyards are grasses, legumes or a mixture of both. Its functions are diverse, including reducing soil erosion, improving soil quality, controlling weeds and diseases and providing nutrients (10, 11). The results of this study indicate that cover crops can have a significant impact on soil fertility (12, 50), easy propagation (9), increased biodiversity (8, 13) and water balance (49).

When compared to vineyards and olive groves, most of the cover crop studies in oil palm plantations are still limited to legume species (14), *Asystasia gangetica* (3, 15), *Nephrolepis biserrata* (4) and identification of cover crop species (16; 17), so it is still difficult to determine suitable weed species as cover crops in mature oil palm plantations. The results of previous studies (18) highlight the need for new research aimed at identifying new weed species for use as cover crops in mature oil palm plantations. In addition, spacing is also required for planting weeds *A. gangetica*, *P. conjugatum* and *N. biserrata* as cover crops so that competition between weeds does not occur in absorbing water and nutrients. Setting the spacing also aims for efficiency in the use of seeds at the time of planting. Therefore, the aim of this study was to obtain the optimum spacing of 3 weed species planted as cover crops in smallholder oil palm plantations.

Materials and Methods

Site description

The study was conducted in a 15-year-old smallholder oil palm plantation in Naga Rejo Village, Galang, Deli Serdang, North Sumatra, Indonesia (3˚29'22" N-98˚52'02" E) (Fig. 1). Naga Rejo village is one of the centers of smallholder oil palm plantations in Deli Serdang The area receives an annual rainfall of 1883 mm and an average annual temperature of 30.35 °C. The duration of precipitation and the average temperature is from January to December. Data of temperature and average annual rainfall during the experimental period are presented in Fig. 2. The soil type is Luvisol according to the World Reference Base for soil resources (19) and is also known as red,

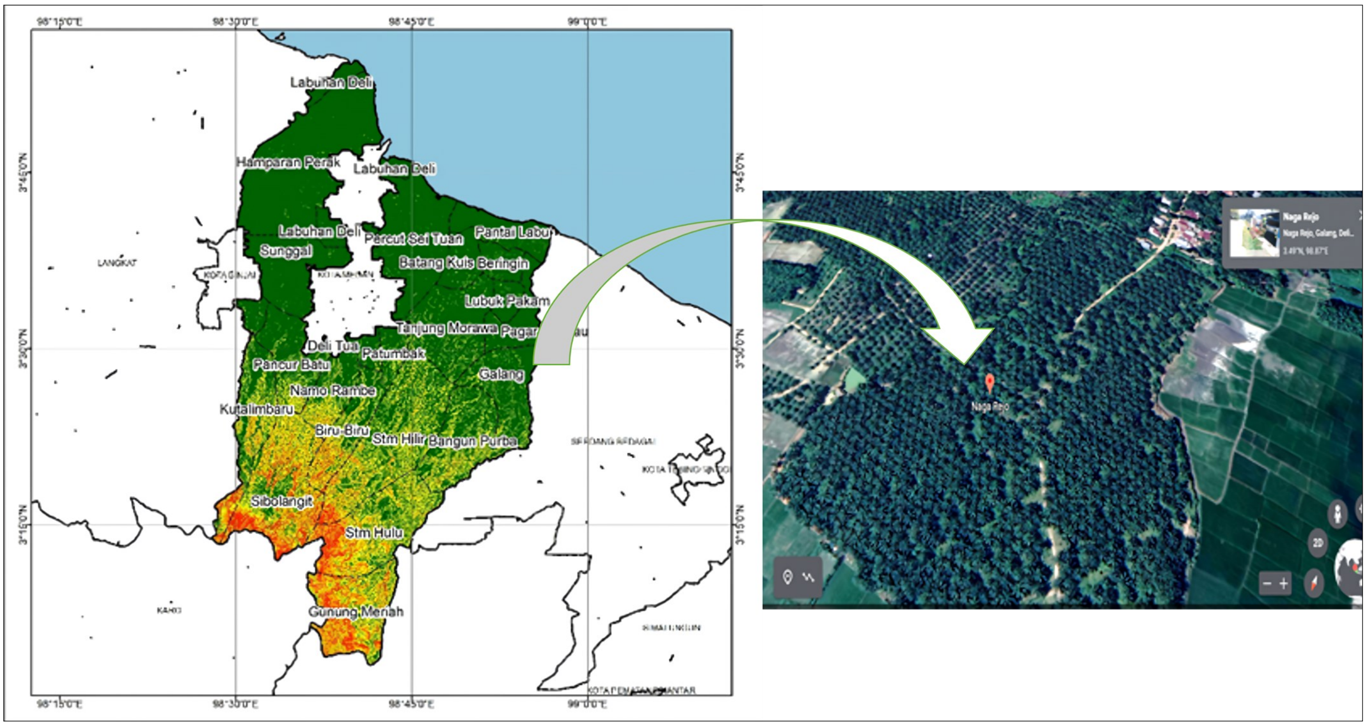

Fig. 1. Research site in smallholder oil palm plantations in Naga Rejo village, Galang, Deli Serdang, Sumatera Utara, Indonesia.

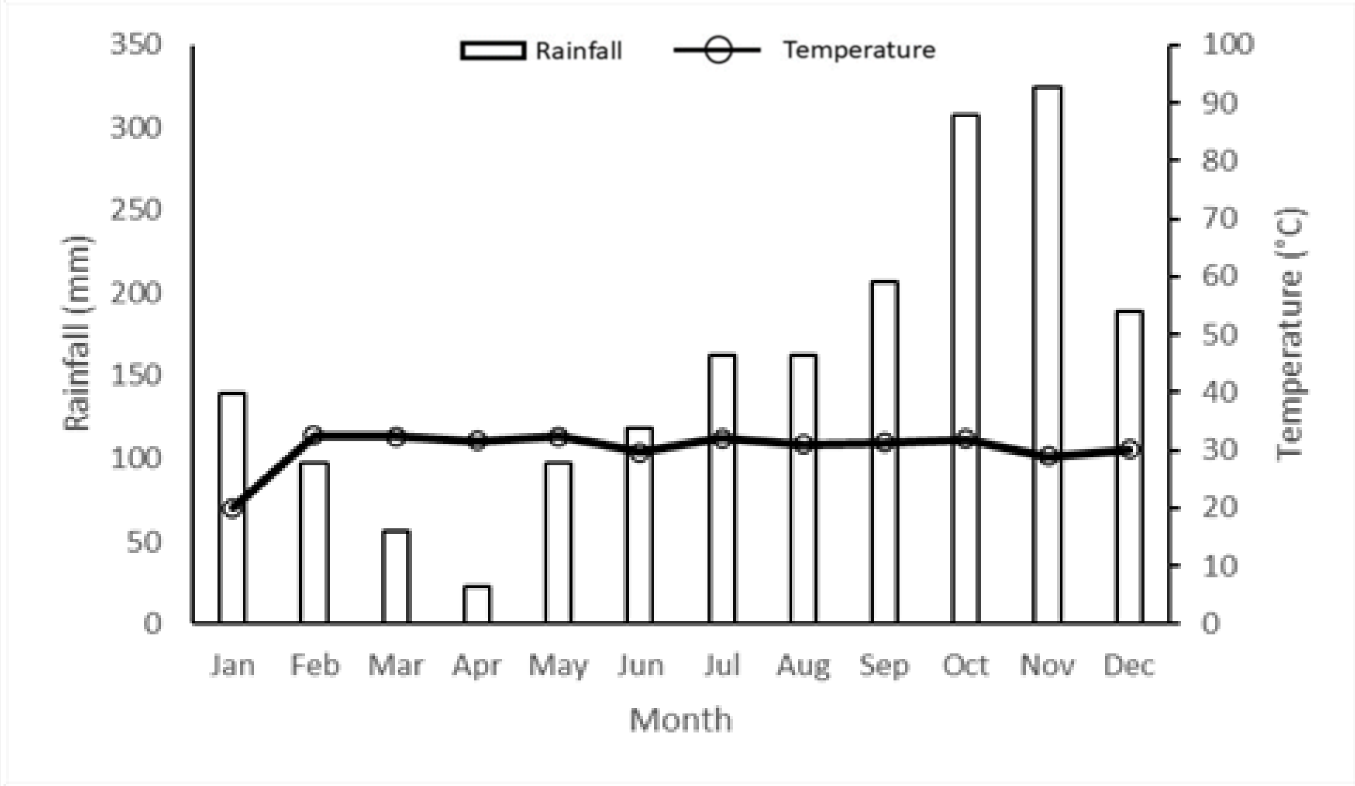

Fig. 2. Rainfall and mean air temperature registered from January to December 2022.

yellow podzolic soil according to the Dudol-Soepraptohardjo soil classification system. (1957-1951). Topsoil chemical properties are soil pH 4.9, soil organic carbon 11000 kg ha^{-1}, N-total 1600 kg ha^{-1}, P-total 800 kg ha^{-1}, P-available 0.66 kg ha^{-1}, K-total 200 kg ha^{-1} and K-available 74.1 kg ha^{-1}.

Experimental design

This research was designed using a Split Plot Design in Randomized Block Design. The first factor was the type of weed (W) as the main plot, which consisted of 3 levels, namely broadleaf weeds *Asystasia gangetica* (L.) T. Anderson (W1), grass weeds *Paspalum conjugatum* Berg. (W2) and the fern weed *Nephrolepis biserrata* Kuntze (W3). The second factor is the spacing (P) as a subplot consisting of 3 levels, namely 10 cm (P1), 20 cm (P2) and 30 cm (P3). Each plot (2 m × 2 m) had three replicates with a spacing of 50 cm between plots and 1 m between replicates. The plant material used was a seed or tiller with the same size and number of leaves obtained from the research location.

The fertilizers applied were urea 150 kg ha^{-1}, SP-36 150 kg ha^{-1} and KCl 50 kg ha^{-1} with a proportion of 375 g $plot^{-1}$ urea, 375 g $plot^{-1}$ SP-36 and 125 g $plot^{-1}$ KCl. Fertilizer is applied at the time of planting by array. Specifically, urea fertilizer is given twice, namely half dose at planting time and half dose at 2 weeks after planting (WAP).

These 3 types of weeds were chosen based on the results of previous research (20) that the dominant weeds under oil palm stands are *A. gangetica* (broad-leaved), *P. conjugatum* (narrow-leafed) and *N. biserrata* (fern). Meanwhile, the 3 spaces used are adjusted to the spaces of the cover crop for legumes (*Mucuna bracteata*), which are usually planted in immature oil palm plantations.

Observed variable

There are 5 variables observed, namely:

Growth percentage (%).

% of growth was observed from 1^{st} week after planting (WAP) to 3 WAP by calculating the number of plants that grew divided by the number of plants that did not grow and multiplied by 100% in each experimental plot.

Land coverage percentage (%).

The land coverage % was calculated by calculating how much soil surface covered from 2 WAP until covered 100% using a square board measuring 0.5 m, and there were small holes measuring 5 cm to represent the amount covered by crops. The land coverage % is calculated using the equation:

$$\%PPT = \frac{A}{B}\ x\ 100\%$$

Where A = number of holes covered by weeds; B = total number of holes.

Leaf area plant^{-1} (cm^2).

The total leaf area of $plant^{-1}$ was calculated at the end of the experiment using the Gravimetric method. The Gravimetric method measured by (1) using leaf patterns (leaf replicas) drawn on plain paper (HVS); (2) the leaf replicas were weighed using an analytical balance; (3) making 10 cm pieces of paper, then weighing them; (4) calculate leaf area using the equation (21):

$$Leaf\ area = \frac{Weight\ of\ leaf\ replicas\ (g)}{Weight\ of\ paper\ 10\ cm x 10\ cm}\ X\ 100\ cm^2$$

Plant dry weight (g).

Plant dry weight was measured at the age of 8 WAP and 16 WAP, which was obtained by weighing each plant part (roots, stems, leaves) that had been dried in an oven at 80 °C for 48 hrs.

Crop growth rate (g/week)

The crop growth rate is measured to determine the growth acceleration of weeds and the measurement uses the following equation:

$$LPT = \frac{W2 - W1}{T2 - T1}$$

Where W2: Dry weight at 12 WAP; W1: dry weight at 8 WAP; T2: Plant age at 12 WAP; T1: Plant age at 8 WAP.

Laboratory analysis

At the end of the study, each plant was harvested using a hoe so that the roots were not damaged and cut off. Soils attached to the roots are cleaned and then air-dried. Plant samples in each treatment plot were oven-dried for 30 min at 105 °C and then heated at 70 °C to constant weight to determine dry matter and nutrient content. The plant samples that had been oven-dried were ground using H_2SO_4-H_2O_2 at 260-270 °C. N content was measured using the Kjeldahl method and P using the yellow vanadomolybdate method (22). The K content was determined using a flame photometer. Plant nutrient uptake was calculated by multiplying plant nutrient content by plant dry weight.

Statistical analysis

Differences in the treatment of weed types and spacing for different observational variables were analysed using 2-way ANOVA followed by the LSD test at a significance level of $P \leq 0.05$ (23).

Results

Growth percentage (%)

The growth % of several types of weeds at various spacings are presented in Table 1. Table 1 shows that several types of weeds planted at different spacings produced the same growth %. Each of the weeds planted, both broadleaf weeds (*A. gangetica*), grasses (*P. conjugatum*) and ferns (*N. biserrata*) with a spacing of 10, 20 and 30 cm, obtained 100% growth. Weeds have the same ability to adapt to the growing environment.

Table 1. Growth percentage (%) of several types of weeds with various spacings in smallholder oil palm plantations.

Main Plot (Weed Type)	Sub Plot (Plant Spacing)	Observation Time (WAP)		
		1 WAP	2 WAP	3 WAP
A. gangetica	10 cm × 10 cm	100	100	100
	20 cm × 20 cm	100	100	100
	30 cm × 30 cm	100	100	100
P. conjugatum	10 cm × 10 cm	100	100	100
	20 cm × 20 cm	100	100	100
	30 cm × 30 cm	100	100	100
N. biserrata	10 cm × 10 cm	100	100	100
	20 cm × 20 cm	100	100	100
	30 cm × 30 cm	100	100	100

Note: Value without notation showed no significant difference (P<0.05) based on 5% LSD test

Land coverage percentage (%)

Independently, weed types and plant spacing had a significant effect on the land coverage % at 2-3 WAP but had no significant effect at 4 WAP. Meanwhile, the interaction between weed types and plant spacing had no significant effect on land coverage % at 2-4 WAP (Table 2).

Table 2. Land coverage percentage (%) of several types of weeds at various plant spacings in smallholder oil palm plantations.

Treatments	Observation Time (WAP)		
	2 WAP	3 WAP	4 WAP
Weed Type			
A. gangetica	54.44±3.40ab	85.00±4.55ab	100±0.71
P. conjugatum	50.00±3.40b	78.89±4.55b	98.77±0.71
N. biserrata	56.67±3.40a	87.78±4.55a	100±0.71
Plant Spacing			
10 cm × 10 cm	74.44±19.57a	100.00±14.73a	100±0.78
20 cm × 20 cm	51.11±19.57b	80.56±14.73b	100±0.78
30 cm × 30 cm	35.56±19.57c	71.11±14.73c	98.65±0.78

Note: Values in the same column and row followed by different notations show significantly different (P<0.05) based on the 5% LSD test

The highest land coverage percentage was found in fern type *N. biserrata,* which was not significantly different from the broadleaf weed *A. gangetica*, namely 56.67% and 54.44% at 2 WAPs and 87.78% and 85.00% at 3 WAPs respectively. The lowest land coverage % was found in grass weed *P. conjugatum*, namely 50.00% at 2 WAPs and 78.89% at 3 WAPs. The land coverage % of *A. gangetica* and *N. biserrata* has reached 100% at 4 WAPs, while *P. conjugatum* has not reached 100%.

Independently, a narrower spacing (10 cm) showed a faster percentage of land coverage and was significantly different from the other spacing (20 and 30 cm). At 3 WAPs, the % of 100% land coverage was achieved at a spacing of 10 cm, which was significantly different from the spacing of 20 cm and 30 cm. A spacing of 20 cm achieves 100% land coverage at 4 WAPs, while a spacing of 30 cm has not reached 100% at 4 WAPs but only achieves 98.65%.

Leaf area plant^{-1} (cm^2)

The effect of spacing had a significant effect ($p < 0.05$) on the leaf area plant^{-1} of the three types of weeds (Table 3). The leaf area of *N. biserrata* was wider than that of *A. gangetica* and *P. conjugatum*, namely 5.99±2.09 cm^2, 4.51±2.09 cm^2 and 1.86±2.09 cm^2 respectively. Wider spacing (30 cm) resulted in a wider leaf area compared to narrower spacing (20 and 10 cm) namely 8.44 ± 3.89 cm^2, 3.01 ± 3.89 cm^2 and 0.90 ± 3.89 cm^2 respectively. In the type of weed *A. gangetica,* wider spacing (30 cm) resulted in a wider leaf area plant^{-1} compared to narrower spacing (20 and 10 cm) namely 9.49 ± 4.48 cm^2, 3.25 ± 4.48 cm^2 and 0.80±4.48 cm^2. For *P. conjugatum* weeds, wider spacing (30 cm) also resulted in a wider leaf area plant^{-1} compared to narrower spacing (20 and 10 cm) namely 4.13 ± 2.03 cm^2, 1.23 ± 2.03 cm^2 and 0.22±2.03 cm^2 respectively. Likewise, for the weed type *N. biserrata*, leaf area $plant^{-1}$ was wider at wide spacing (30 cm) compared to narrow spacing (20 and 10 cm) namely 11.72 ± 5.17 cm^2, 4.58 ± 5.17 cm^2 and 1.68±5.17 cm^2.

Table 3. Leaf area per plant (cm^2) of several types of weeds at various plant spacings in smallholder oil palm plantations.

Treatments	Weed Type (W)			Average P
	A. gangetica	*P. conjugatum*	*N. biserrata*	
Plant Spacing (P)				
10 cm × 10 cm	0.80±4.48c	0.22±2.03c	1.68±5.17c	0.90±3.89c
20 cm × 20 cm	3.25±4.48b	1.23±2.03b	4.58±5.17b	3.01±3.89b
30 cm × 30 cm	9.49±4.48a	4.13±2.03b	11.72±5.17a	8.44±3.89a
Average W	4.51±2.09a	1.86±2.09b	5.99±2.09a	

Note: Values in the same column and row followed by different notations show significantly different (P<0.05) based on the 5% LSD test.

When viewed from the type of weeds, it can be seen that the widest leaf area per plant was found in the type of fern weed (*N. biserrata*), which was not significantly different from the type of broadleaf weed (*A. gangetica*), but significantly different from the type of grass weed (*P. conjugatum*) namely 8.44 cm^2, 3.01 cm^2 and 0.91 cm^2 respectively.

Plant dry weight (g)

The effect of weed types and spacing, as well as the combination of weed types and spacing, had a significant effect (p <0.05) on the plant dry weight of several types of weeds (Table 4). The dry weight of *N. biserrata* was heavier and significantly different from the dry weight of *A. gangetica* and *P. conjugatum*, which were 16.77 ± 5.32 g, 13.43 ± 5.32 g and 6.35 ± 5.32 g respectively. The plant spacing treatment showed that the plant dry weight was heavier at 10 cm spacing, which was not significantly different from 30 cm spacing but significantly different from 20 cm spacing, namely 12.71 ± 0.57 g, 12.25 ± 0.57 g and 11.58±0.57 g.

Based on weed type and spacing, the dry weight of *N. biserrata* was heavier at a narrow spacing of 10 cm compared to spacing of 20 and 30 cm is 17.36±0.65 g, 16.88±0.65 g and 16.07±0.65 g respectively. Likewise, for the type of weed *P. conjugatum*, plant dry weight was heavier at a spacing of 10 cm compared to a spacing of 20 and 30 cm namely 8.01 ± 1.45 g, 5.67 ± 1.45 g and 5.36 ± 1.45 g respectively, while weed *A gangetica* was heavier at a spacing of 30 cm compared to a spacing of 10 and 20 cm namely 15.31±1.66 g, 12.77±1.66 g and 12.20±1.66 g (Table 4).

Table 4. Plant dry weight (g) of several types of weeds at various plant spacings in smallholder oil palm plantations.

Treatments	Weed Type (W)			Average P
	A. gangetica	*P. conjugatum*	*N. biserrata*	
Plant Spacing (P)				
10 cm × 10 cm	12.77±1.66b	8.01±1.45c	17.36±0.65a	12.71±0.57a
20 cm × 20 cm	12.20±1.66b	5.67±1.45d	16.88±0.65a	11.58±0.57b
30 cm × 30 cm	15.31±1.66a	5.36±1.45d	16.07±0.65a	12.25±0.57ab
Average W	13.43±5.32b	6.35±5.32c	16.77±5.32a	

Note: Values in the same column and row followed by different notations show significantly different (P<0.05) based on the 5% LSD test.

Crop growth rate (g week $^{-1}$)

The effect of weed types and spacing, as well as the interaction of weed types and spacing, had a significant effect (p <0.05) on the crop growth rate of several weed species (Table 5).

Table 5. Crop growth rate (g/week) of several types of weeds with various spacing in smallholder oil palm plantations.

Treatments	Weed Type (W)			Average P
	A. gangetica	*P. conjugatum*	*N. biserrata*	
Plant Spacing (P)				
10 cm × 10 cm	1.48±0.18b	0.94±0.17c	1.97±0.09a	1.46±0.58a
20 cm × 20 cm	1.39±0.18b	0.67±0.17c	1.88±0.09ab	1.31±0.58b
30 cm × 30 cm	1.73±0.18a	0.62±0.17c	1.80±0.09b	1.38±0.58ab
Average W	1.53±0.08b	0.74±0.08c	1.88±0.08a	

Note: Values in the same column and row followed by different notations show significantly different (P<0.05) based on the 5% LSD test.

The crop growth rate of *N. biserrata* was faster than that of *A. gangetica* and *P. conjugatum* at 1.88±0.08 g $week^{-1}$, 1.53±0.08 g $week^{-1}$ and 0.74±0.08 g $week^{-1}$ respectively. In the treatment of spacing, it was shown that spacing of 10 cm resulted in a faster crop growth rate compared to spacing of 30 cm and 20 cm namely 1.46 ± 0.58 g/week, 1.38 ± 0.58 g/week and 1.31 ± 0.58 g/week.

Based on weed type and spacing, the crop growth rate of *N. biserrata* was faster at 10 cm spacing compared to 20 and 30 cm wide spacing namely 1.97 g $week^{-1}$, 1.88 g $week^{-1}$ and 1.80 g $week^{-1}$. Likewise, the crop growth rate of *P. conjugatum* was faster at 10 cm spacing compared to 20 and 30 cm wide spacing, namely 0.94 g $week^{-1}$, 0.67 g $week^{-1}$ and 0.62 g $week^{-1}$, while the crop growth rate of *A. gangetica* was faster at a spacing of 30 cm compared to a spacing of 10 and 20 cm, namely 1.73 g $week^{-1}$, 1.48 g $week^{-1}$ and 1.39 g $week^{-1}$ respectively (Table 5).

Nutrient uptake of N, P, K (kg ha^{-1})

The type of weeds and spacing, as well as the combination of weed types and spacing, had a significant effect ($p < 0.05$) on nutrient uptake of N (Fig. 3) and K (Fig. 5) but had no significant effect on nutrient uptake of P (Fig. 4). N and K nutrient uptake in *A. gangetica* was higher at 30 cm spacing compared to 10 and 20 cm spacing. Meanwhile, for *P. conjugatum* and *N. biserrata*, N and K nutrient uptake was higher at 10 cm spacing compared to 20 and 30 cm spacing (Fig. 3 and Fig. 5).

Based on the type of weed, nutrient uptake of N (Fig. 3), P (Fig. 4) and K (Fig. 5) in *A. gangetica* was higher than that of *N. biserrata* and *P. conjugatum*.

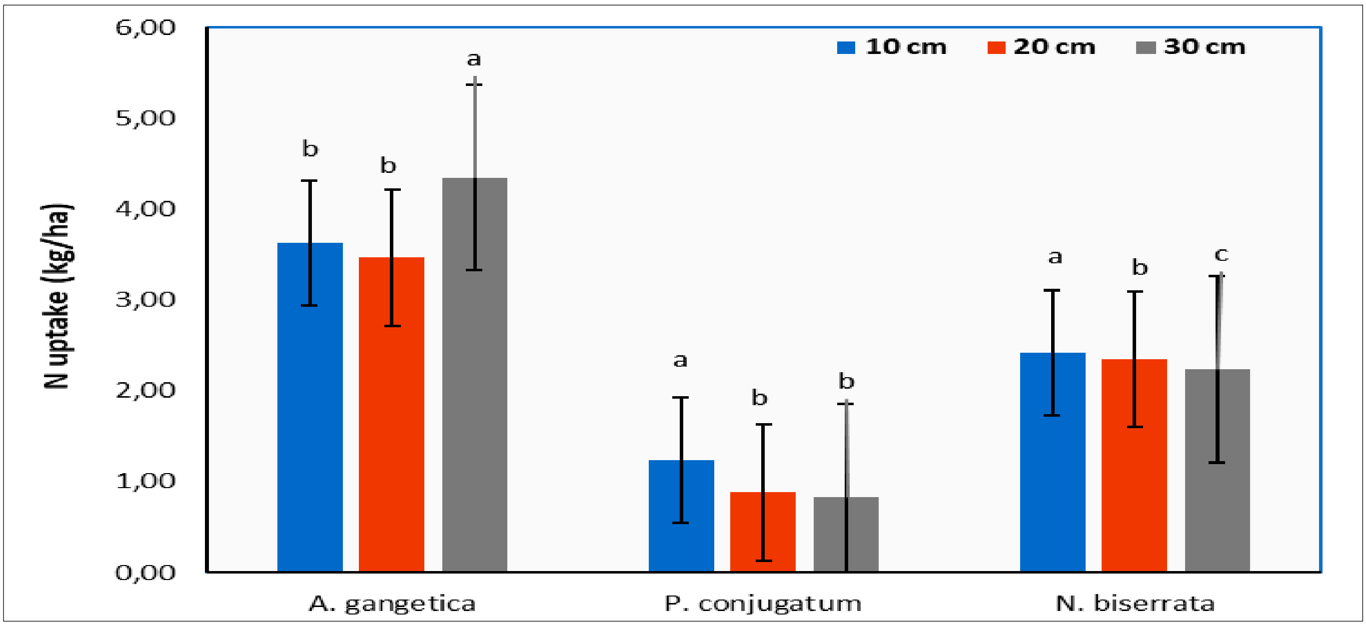

Fig. 3. Uptake of N from several types of weeds with different plant spacing. Means with different letters are significantly different based on the LSD test (α= 0.05).

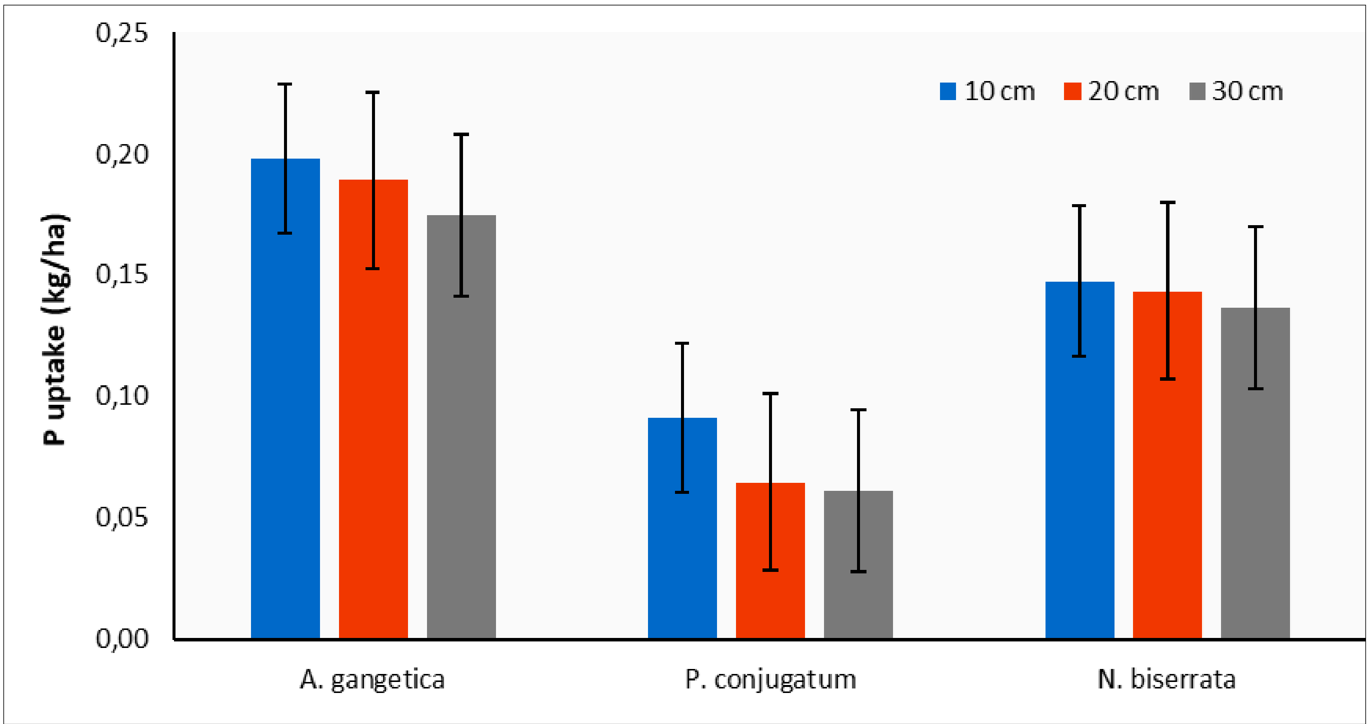

Fig. 4. Uptake of P from several types of weeds with different plant spacing. Means without letters are not significantly different based on the LSD test (α= 0.05).

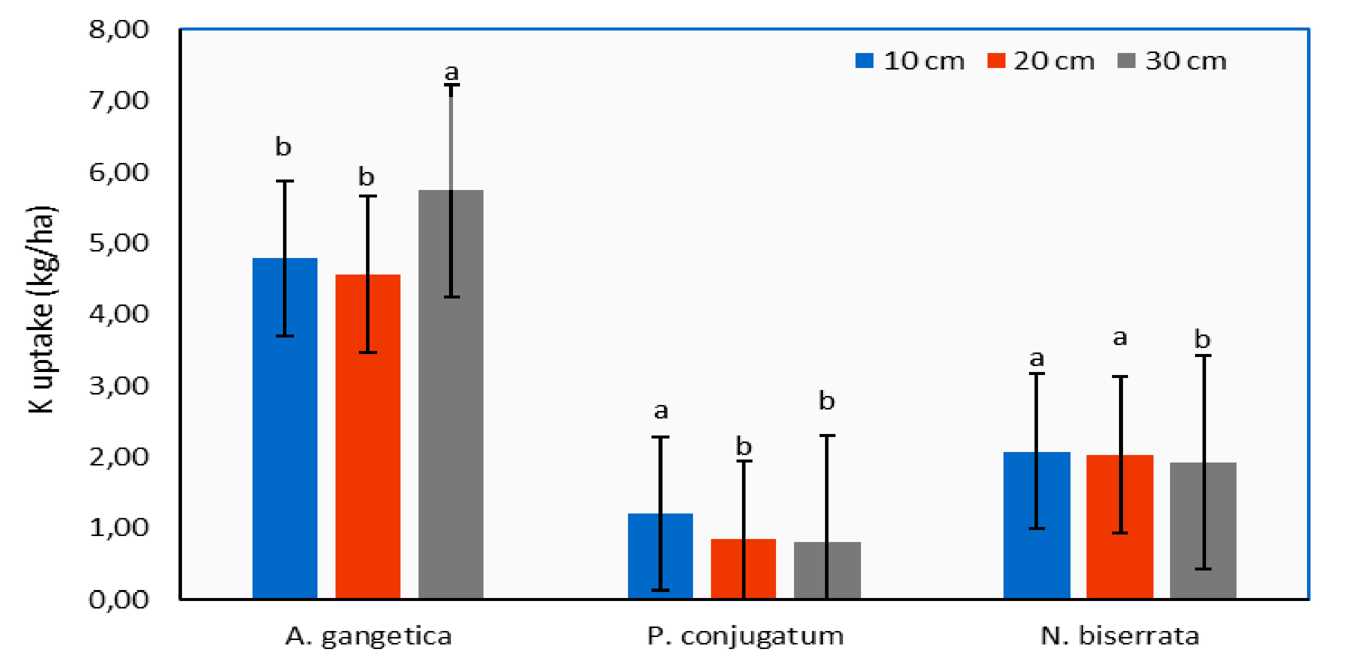

Fig. 5. Uptake of K from several types of weeds with different plant spacing. Means with different letters are significantly differen t based on the LSD test (α= 0.05).

Discussion

The highest land coverage % was found in the treatment of the fern weed *N. biserrata,* which was not significantly different from the broadleaf weed *A. gangetica*, namely 56.67% and 54.44% in 2 WAPs, 87.78% and 85.00% in 3 WAPs respectively. While the smallest land coverage % was obtained in the treatment of grass weeds*P. conjugatum*, namely 50.00% in 2 WAPs and 78.89% in 3 WAPs. The land coverage % for *A. gangetica* and *N. biserrata* had reached 100% in 4 WAPs, while *P. conjugatum* had not yet reached 100%. This is because the organ structure of grass weeds is different from that of broadleaf weeds and ferns. *N. biserrata* is a fern weed with broad leaves and a broad crown, similar to *A. gangetica,* which is a broadleaf weed with a broad crown. Meanwhile, *P. conjugatum* is a grassy weed with narrow leaves and a narrower crown (24). It was stated that plant architectural characteristics, such as the number and geometry of organs that describe their shape and position in the plant and canopy are genotype specific (25). Furthermore, it was again stated that plant height, branch length, branch angle, main inflorescence length, leaf angle and number of branches per plant determine plant architecture and affect plant growth components (26).

Narrower spacing (10 cm) showed a faster land coverage % and was significantly different from the other spacing (20 and 30 cm). At 3 WAPs, the land coverage % had reached 100% at a spacing of 10 cm and a spacing of 20 cm, the land coverage % had reached 100% at 4 WAPs, while a spacing of 30 cm only reached 98.65% at 4 WAPs, in line with the results of research conducted (15, 18) which showed that the % of weed cover was faster at a spacing of 10 cm compared to wider spacing. This is due to the denser spacing. The plant population per unit of land is also greater, so that the number of crowns that cover each other is also greater. It was stated that at narrower spacings, the population per unit of land will be more than those with wider spacings so that they cover the soil more quickly (27). Based on this result, it was found that the optimum spacing to obtain 100% land coverage more quickly is to plant cover crops using a spacing of 10 cm.

The leaf area per plant was wider in *N. biserrata* compared to *A. gangetica* and *P. conjugatum* due to differences in the leaf architecture of each weed. *N. biserrata* has lanceolate-shaped compound leaves arranged in single, parallel pinnate, pinnate leaf veins with a leaf length of 120-160 cm and a leaf width of 19-25 cm (28). The leaves of *A. gangetica* are oval, grow in pairs, and face each other with a leaf length of 5 cm and a width of 3.5 cm (29), while the leaves of *P. conjugatum* are ribbon-shaped (ligulatus) with pointed leaf tips (acutus) and hairy along the edges and on the surface, leaf base rounded (rotundatus) with leaves ranging from 8-20 cm long and 5-12 mm wide (24).

Wider spacing (30 cm) results in a wider leaf area per plant. This is due to less competition between plants for space, nutrients and light so that plants are able to grow more optimally compared to plants planted with a spacing of 20 and 10 cm. It was stated that plants planted with wider spacing showed more horizontal and continuous vegetative growth due to smaller population pressure per land area (30), in line with the results of an earlier study which showed that the leaf area of cluster bean was wider at wider plant spacings (27).

Plant dry weight was heavier at wider spacing (30 cm) for *A. gangetica* weeds, whereas for *P. conjugatum* and *N. biserrata* weeds, plant dry weight was heavier at narrower spacing (10 cm). This is because the leaf area per plant of *A. gangetica* is also wider at wider spacing (Table 3). *A. gangetica* is a plant with many branches, so the wider leaves per plant will result in a heavier plant dry weight because there is no competition for solar radiation for photosynthesis between plant leaves. It was stated that plant photosynthesis and plant dry weight are closely related to the interception of the photosynthetically active radiation (PAR) canopy (31). Reasonable spacing is the basis for creating a successful population structure that includes the desired leaf area index and makes full use of light energy to increase the photosynthetic capacity of the leaves (32).

For *P. conjugatum* and *N. biserrata* weeds, plant dry weight was heavier at narrow spacing compared to wider spacing (Table 4), although the leaf area per plant was wider at wide spacing (Table 3). This is due to the canopy structure of the *P. conjugatum* and *N. biserrata* plants, which shade each other, thereby reducing the interception of solar radiation by each leaf, which causes a decrease in the rate of plant photosynthesis. Wide plant spacing will reduce the ability of light to penetrate the lower canopy (33), thereby significantly reducing plant dry weight (34).

The faster growth rate of *A. gangetica* at wider spacing (30 cm) compared to narrower spacings (10 and 20 cm) is because *A. gangetica* is a type of perennial weed with many branches, so it requires space, nutrients and optimum light for growth. This can be seen from the leaf area per plant of *A. gangetica,* which was also wider at wider spacing (Table 3). According to one report, leaves are the main photosynthetic organs and photosynthetic capacity can be increased by increasing leaf area, so plant dry weight will increase (Table 4) and plant growth rate will also increase (35). Furthermore, it was also stated that a narrower spacing would accelerate leaf senescence, reduce the net photosynthetic rate and assimilate the availability of photosynthate for plant growth and development (36).

P. conjugatum and *N. biserrata*, the crop growth rate was faster at narrower spacing compared to wider spacing (Table 5). This is because *P. conjugatum* and *N. biserrata* have different canopy architecture from *A. gangetica*. *P. conjugatum* and *N. biserrata* have compact branches, while *A. gangetica* has spreading branches. It was stated that the branch angle is a key determinant for plant ideotypes as it influences planting density and further increases biomass yield by influencing photosynthetic efficiency (37). Reports are also revealed that plants with compact branches, when planted with wide spacing (33), will reduce the ability of light to penetrate the lower leaves, causing the lower leaves to experience premature senescence (38) and reducing the radiation utilization efficiency (RUE) (39). In the end, it will reduce the plant growth rate because the dry weight of the plant will decrease in line with the results of a study, which showed that plants with compact branches grow faster at narrow spacings than those with wide spacings (40).

Nutrient uptake of N and K (Fig. 3 and Fig. 5) in *A. gangetica* was higher at wide spacing (30 cm) compared to narrow spacing (10 and 20 cm) due to the wide canopy architecture of *A. gangetica* so that with wide spacing it will reduce competition between plants to space, light and nutrients. Plants may have suitable space for root extension and absorption of nutrients from a large area compared to plants with narrow spacing. This finding is in line with studies (27, 41, 42), which showed that plant nutrient uptake was higher at wider planting densities compared to lower planting densities.

Nutrient uptake in *P. conjugatum* and *N. biserrata*, N and K was higher at narrow spacing due to the overlapping canopy architecture of *P. conjugatum* and *N. biserrata*. According to one report, narrow spacing was the most common method chosen to increase photosynthetic capacity by increasing the available solar radiation intercept in plants with overlapping canopy architecture in order to increase plant dry weight (43). Narrow spacing significantly increases nutrient uptake in adjacent overlapping crop areas, especially when neighboring plants exhibit similar root architecture (44). N and K uptake mainly depend on plant dry weight, spatial distribution of roots and nutrient uptake rate per unit root (45). This is in line with the results of research (46), which showed that an increase in plant dry weight would increase plant nutrient uptake.

Conclusion

The results showed that the three types of weeds had different land coverage rates. *N. biserrata* and *A. gangetica* in 4 WAPs had covered 100% of the land, while *P. conjugatum* had not covered 100% of the land in 4 WAPs. 100% land coverage was achieved when 3 WAPs were planted at 10 cm spacing and 4 WAPs at 20 cm spacing, while 30 cm spacing had not reached 100% at 4 WAPs. The highest leaf area of *N. biserrata*, *P. conjugatum* and *A. gangetica* was obtained at a spacing of 30 cm. The highest dry weight, growth rate, N and K nutrient uptake in *N. biserrata* and *P. conjugatum* were obtained at a spacing of 10 cm, while for *A. gangetica* at a spacing of 30 cm. This shows the optimum spacing depending on the weed species used. The optimum spacing for *A. gangetica* (broad leaf) is 30 cm, while for *P. conjugatum* (grasses) and *N. biserrata* (ferns) is 10 cm.

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Authors contributions

YA conducted the research design, participated in data collection and drafted the manuscript. NN performed statistical analysis of data. YP and HS participated in the preparation and alignment of the manuscript, as well as general coordination and corresponding to editor. MSR and MA participated in data collection. All authors read and approved the final manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

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