**BIODIVERSITAS**
Volume 25, Number 10, October 2024
Pages: 3909-3919

ISSN: 1412-033X
E-ISSN: 2085-4722
DOI: 10.13057/biodiv/d251051

# The effect of planting distance engineering treatment on the morphophysiology and yield of soybean varieties integrated with oil palm

**WAGINO[1], ABDUL RAUF[2,♥], CHAIRANI HANUM[2], RAHMANTA[3]**
[1]Faculty of Agriculture, Doctoral Program of Agricultural Sciences, Universitas Sumatera Utara. Jl. Dr. A. Sofian No. 3, Medan 20155, North Sumatra, Indonesia
[2]Faculty of Agriculture, Universitas Sumatera Utara. Jl. Dr. A. Sofian No. 3, Medan 20155, North Sumatra, Indonesia. Tel.: +62-618-213-236, ♥email: a.raufismail@gmail.com
[3]Department of Agribusiness, Faculty of Agriculture, Universitas Sumatera Utara. Jl. Dr. A. Sofian No. 3, Medan 20155, North Sumatra, Indonesia

Manuscript received: 3 September 2024. Revision accepted: 29 October 2024.

**Abstract.** *Wagino, Rauf A, Hanum C, Rahmanta. 2024. The effect of planting distance engineering treatment on the morphophysiology and yield of soybean varieties integrated with oil palm. Biodiversitas 25: 3909-3919.* The use of inter-land in oil palm plantations of immature plants is commonly studied, and the use in productive oil palm plantations distance has not been investigated. The research aimed to evaluate the productivity, environmental characteristics, and economic value of oil palm and soybean integration. A Split-Plot Design was used with the main plot consisted oil palm planting, the sub-plot was soybean planting repeated three times. The results that light intensity unmodified oil palm planting distance system decreased by 28% compared to the modified. The treatment of oil palm planting distance modification had a significant effect on the amount of leaf chlorophyll, seed weight per plant (11.49 g), weight of 100 seeds (18.29 g), production per-plot (993.55 g), and Dena 1 (692.90 g). The Land Equivalency Ratio (LER) was >1 (1.06) integration of Dena 1 soybean variety with oil palm planting distance engineering and an R/C value of 1.79, providing greater benefits compared to the monoculture planting system. The system also provided improvements to the environment by an increase in nitrogen (N) nutrient levels and soil organic carbon (C) levels. The oil palm planting distance engineering model could be a solution to increase sustainable soybean production in Indonesia.

**Keywords:** Integrated, land equivalency value, modification, oil palm, soybean

## INTRODUCTION

Soybeans (*Glycine max* (L.) Merr.) are important food and animal feed crops in the world. Globally, the production is estimated at 353.5 million tons, with a harvest of over 127.0 million ha, almost doubling the yield in 2001 (Zhang et al. 2023). According to Vogel et al. (2021), soybean is the world's most important source of protein and vegetable oil, both for human consumption and animal feed. The projected increase in total production capable of meeting the demands of the growing world population from 2021 to 2029 is 17%. This plant contains amino acids that are nutritionally balanced for humans (Guo et al. 2022). Soybean has traditionally been used to make tofu, soy milk, soy milk powder, soybean oil, tempeh, soy sauce, and recently as an alternative substitute for meat (Wang et al. 2024). The productivity and profitability of soybean farming remain low compared to other commodities, and the expansion of production areas is limited (Zhang et al. 2024a). Therefore, production is still unable to meet domestic needs, leading to frequent importation. Several agronomic factors, such as superior seed, climate, and other abiotic factors, constrain domestic production. Soybean plant productivity is related to the decreasing land area, and one of the options offered is to use the land between oil palm plants, which is relatively large and rarely used.

Data BPS (2024) reports that soybean imports in Indonesia reached 2.32 million tons with a value of US$ 1.63 billion in 2022. This amount decreased by 6.63% compared to the previous year, which was 2.49 million tons with a value of US$ 1.48 billion (Figure 1).

Looking at the trend, imports are indeed fluctuating, but based on the volume, Indonesia has imported the most soybeans in the last decade, reaching 2.67 million tons in 2017 and 2019. Soybean imports by region came from 25 countries in 2022; the largest was from the United States, reaching 1.93 million tons with a value of US$1.37 billion. According to Krisdiana et al. (2021), prices can compete with other crops when productivity and prices are higher than in current conditions.

Oil palm plantations are expanding every year, and monoculture planting systems require large areas of land; there is much empty space between oil palm rows, which has the potential to cultivate shade-tolerant plants. Therefore, integration can be applied to fill rows in oil palm plantations, reduce weed growth, and save on herbicide use. Efficient management of oil palm as the main crop with many plant species will contribute positively to increasing biodiversity and ecosystem function (Hood et al. 2020). Soil samples from integrated oil palm plantations have a very high potential for absorbing carbon (C), and the integration system can increase farmers' income (Purwanto et al. 2020). Supported by research by Wagino et al. (2021) tested several varieties on 4-year-old oil palm stands, and the Dena 1 soybean variety had the highest seed weight/plant, number of seeds/plant and seed production per plot compared to others; this shows its ability to adapt to shade in oil palm stands.

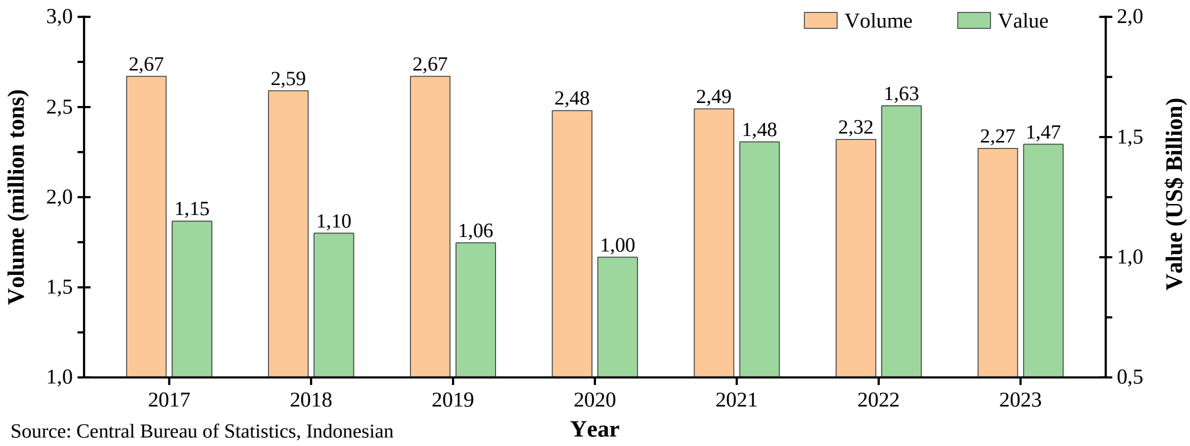


**Figure 1.** Indonesian soybean imports 2017-2023

National soybean production still needs to be increased but is constrained by land availability. Increasing production through integration with oil palm can contribute to sustainability and enhance soil fertility in oil palm lands because soybeans can fix N. Generally, commercial oil palm plantations are currently carried out with a monoculture planting pattern. Soybean and oil palm integration is feasible when oil palm plants are not yet producing (TBM) or modifying planting distances in the field. Intercropping patterns or integration models will cause competition for environmental natural resources such as water, light, and nutrients, which in turn can impact growth and production, ensuring the sustainability of plant cultivation. Therefore, this research aimed to determine the productivity of soybeans and the economic value cultivated on land between oil palm plants that are already producing (4 years old) with planting distance engineering.

## MATERIALS AND METHODS

### Research location and time

This research was conducted from April to July 2022 at the oil palm plantation of the Indonesian Oil Palm Technology Institute (ITSI), Deli Serdang District, North Sumatra Province. Anatomical analysis of stomata, leaf thickness, and root was conducted at the research hub Laboratory in Malang, Indonesia.

### Research materials and tools

The materials used in this research were seeds of two soybean varieties (Dena 1, Grobogan), urea fertilizer, TSP, KCL, alcohol, fungicide (Dithane M-45 active ingredient mancozeb), and insecticide (active ingredient decis deltamethrin). Meanwhile, the tools used were hoes, ropes, meters, SPAD (Soil Plant Analysis Development) chlorophyll meters, scissors, sliding microtomes, razor blades, cork rods, safranin, glycerin, object glasses and cover glasses, clear tape, clear nail polish, object glasses, microscopes, analytical scales, sprayers, laptops, cameras, and stationery to conduct observations.

### Procedures

This research was conducted by planting and observing soybean varieties Dena 1 and Grobogan planted with an integrated system in a 4-year-old oil palm plantation. All treatments were repeated three times using a Split-Plot Design with three factors (Figures 2 and 3). First, the main plot or oil palm planting distance system (J) has two levels, namely standard oil palm planting distance equilateral triangle 9 m × 9 m ($J_1$) and modified oil palm planting distance 9 m × 15.6 m ($J_2$). Second, the sub-plot or soybean planting distance system has four planting distances, namely 30 cm × 20 cm ($T_1$), 35 cm × 25 cm ($T_2$), 40 cm × 15 cm ($T_3$), and 40 cm × 20 cm ($T_4$). Third, another sub-plot, or soybean varieties, consists of two varieties, namely Dena 1 ($V_1$) and Grobogan ($V_2$). The experimental plot size was 2 m × 3 m, two seeds were planted per hole, and planting was carried out on the same date for all three experiments. Thinning of planting distance was conducted to optimize growth space, reduce competition between plants, and increase access to sunlight, ventilation, and air circulation. According to previous research, thinning helped reduce the risk of *Ganoderma boninense* Pat. disease and *Oryctes rhinoceros* (Linnaeus, 1758) pests attacking oil palm plants (Saragih et al. 2021; Suwandi et al. 2024). Monoculture planting was used to compare and determine the efficiency of integration with modification of oil palm planting distance, while weeds were controlled manually. The design of soybean-oil palm integration system with planting distance engineering is described below.

The intercropping design continues to develop for agroecosystems, where integration is the dominant form of agriculture due to limited land, specifically for soybean cultivation. The design aims to create sustainable oil palm plantations, with intercropping of soybean cultivation or other crops, by providing open space from the loss of 1 row. Hence, the planting distance becomes 9 m × 15.6 m. The intercropping system allows the cultivation of several crops simultaneously in an agroecological approach for sustainable agricultural intensification in oil palm plantations (Pelech et al. 2023).

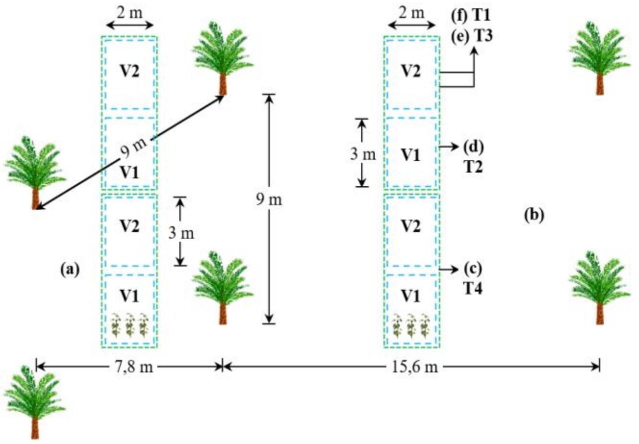


**Figure 2.** Layout and plant spacing of soybean intercropping with oil palm. Main plot: (a) Standard oil palm planting distance 9 m × 9 m ($J_1$); (b) Modified oil palm planting distance 9 m × 15.6 m ($J_2$); Sub-plots: (c,d,e,f) soybean planting distance ($T_4$, $T_2$, $T_3$, $T_1$); each consists of sub-plots: soybean varieties Dena 1 ($V_1$) and Grobogan ($V_2$)

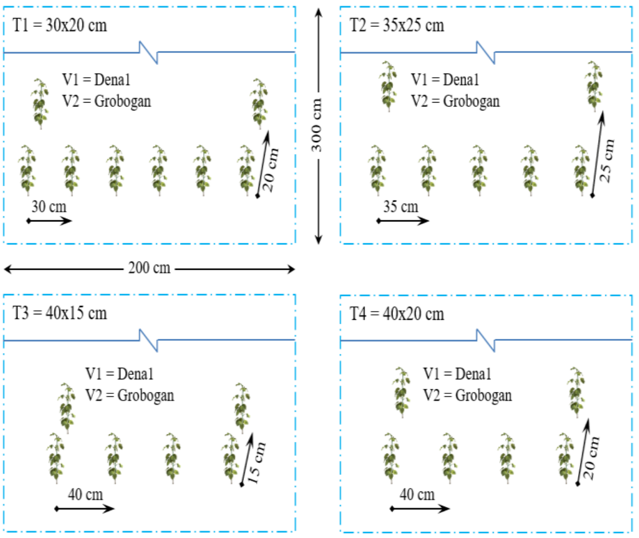


**Figure 3.** Illustration of the experimental design for variations in soybean planting distance in sub-plots ($T_1$, $T_2$, $T_3$, $T_4$), each consisting of sub-plots of soybean varieties ($V_1$, $V_2$)

*Observation*

Research observations include soil nutrient absorption, oil palm leaf, stomata and leaf thickness, soybean root, and agronomic character data obtained by observing plant height (cm), flowering age (days), harvest age (days), number of seeds per-plant (seeds), seed weight per plant (g), dry plant weight (g), weight of 100 seeds (g), production per-plot (g), and the amount of chlorophyll in soybean leaf.

*Anatomy of soybean leaf and root*

The paraffin method was used for root anatomy observation, leaf thickness, and stomata. The observation was carried out by taking one from each variety and then one plant from the standard, modified, and monoculture oil palm planting systems. The root and leaf thickness preparations were transferred in 70% alcohol and cut to a size of approximately 0.5 cm × 1 cm. Subsequently, the specimen was inserted into the prepared cassava stem cork. The cassava stem cork + specimen was placed into the sliding microtome holder, and the specimen was cut using a microtome with a thickness of approximately 100 microns. Using a small brush, the pieces were collected and placed in a petri dish filled with water to check the thickness of the slices. The thinnest slices were selected and then soaked in safranin solution for approximately 2-4 minutes. The slices were transferred to the object glass, and sufficient glycerin was added and covered using a cover glass. The sample was labelled and prepared for microscope observation.

*Land Equivalent Ratio (LER)*

Economic feasibility analysis is an important variable for the productivity of soybean intercropping systems with oil palm. A comparison of monoculture planting systems is needed to obtain the same results as integration. This was calculated using the Land Equivalent Ratio (LER) (Harsono et al. 2020).

$$\text{LER} = \sum_{i=1}^{n} \frac{Xi}{Yi}$$

Where :

$X_i$ : Yield of each plant combination per hectare of intercrops in oil palm (tons)

$Y_i$ : Yield of each crop per hectare in oil palm intercropping monoculture system (tons)

Criteria : LER>1 means the intercropping system is efficient, and LER≤1 means the intercropping system is inefficient.

*Oil palm production and income*

Fresh Fruit Bunches (FFB) that met the harvest maturity criteria on oil palm sample trees at the research location were harvested and then weighed. Production was calculated during the research until the 3-month-old soybean harvest. Total revenue from soybean-oil palm integration compared to the monoculture planting system was calculated based on Noor's formula (2007), namely: TR = P Q; where TR is Total Revenue (IDR), P is the price (IDR $kg^{-1}$), and Q is the number of production units (kg).

Economic feasibility analysis was performed using the R/C ratio, which is the comparison between total revenue and total costs, with the formula:

A = TR/TC

Where:

A : R/C ratio

TR : Total revenue (income)

TC : Total cost

Economic feasibility criteria, if:

R/C ratio>1 then farming is said to be feasible/ profitable

R/C ratio<1, then the farming business is said to be unviable/loss-making

R/C ratio = then the farming business is said to be breaking even (neither making a profit nor a loss)

**Data analysis**

Analysis of Variance (ANOVA) was performed using the F Test, and when a significant difference was found, the analysis was continued with the Tukey test at a 95% confidence level. All analyses were carried out using IBM SPSS Statistics v.22.0 application (SPSS Inc. Chicago, IL, USA), Minitab® 21.3 Software.

## RESULTS AND DISCUSSION

**Environmental conditions of the research location**

Data from BMKG (Meteorology, Climatology, and Geophysics Agency) Sampali, Deli Serdang District, showed that the average rainfall during the research period was 340.5 mm month$^{-1}$ and the average rainy days were 19 days month$^{-1}$. The altitude was 25 m above sea level, and the predominant soil type was alluvial.

The research location had a tropical climate with rainy and dry seasons, average rainfall of 206 mm month$^{-1}$, humidity of 83.5%, and minimum temperature of 23.9°C and 32.6°C, as presented in Figure 4.

The initial planting carried out during the dry season resulted in less than optimal growth at the start of the vegetative phase. Accumulated rainfall during the research reached 340.5 mm with 19 rainy days. Low rain at the start of planting was overcome by daily watering. After plants passed the critical phase of water requirements, intensive watering was not carried out because the water requirements were met by rainfall.

There was interception of sunlight under oil palm stands in standard and modified planting spacing systems. Differences in light intensity were observed in the research plots of blocks I, II, and III of the standard planting system, reaching 15.750 lux, 22.810 lux, and 22.500 lux, respectively, or with a percentage of light intensity of 28%. The intensity received by soybean plants was significantly lower than the modified oil palm planting spacing system.

The average light intensity in the research plot of standard oil palm planting distance was 28%, and in the oil palm fence, it was 21%. Meanwhile, in the modified group, the light intensity was 72%, and oil palm was 57%. As stated by Staniak et al. (2023), reduced light intensity limits the amount of photosynthate supply to the generative organs of soybean plants, thereby lowering production. An abiotic factor that is very important for the growth of soybean and oil palm plants is sunlight. Changes in light intensity alter the characteristics of photosynthesis, which will have an impact on increasing plant height (Khalid et al. 2019).

The results in Table 2 showed that soil nutrients varied between very low and very high (phosphorus and potassium). Compared to the modified oil palm planting distance treatment, the standard had very low nutrients, underscoring the need for organic or inorganic fertilization to support the growth of soybean plants.

The average pH at a depth of 0-20 cm was 4.91 to 5.11, while at a depth of 20-40 cm, it was 4.96 to 5.09. Data analysis showed that acidity tended to decrease with increasing soil depth, but at a depth of 0-20 cm, pH was normal, even though the appropriate value for soybean growth ranged from 5.8-7. As stated by Enesi et al. (2023), acidic soils limit the potential for plant production due to the low availability of base cations as well as excess hydrogen ($H^+$) and aluminum ($Al^{3+}$) in exchangeable forms. This affects beneficial microorganisms and reduces root growth, which limits nutrient and water absorption, thereby causing plant growth and soybean yields to decrease. $Al^{3+}$ toxicity is among the main limiting factors for soybean plant production in acidic soils because it inhibits the division and elongation of root cells, reducing water and nutrient absorption, along with poor nodulation. Due to the detrimental nature of this condition to soybean cultivation, necessary measures are required to increase pH.

N nutrient content at a depth of 0-20 cm was very low, and a similar result was observed at a depth of 20-40 cm in oil palm plants with standard planting distance. However, oil palm planting distance engineering and monoculture showed medium N nutrient criteria ranging from 0.21-0.24. One of the important elements for the growth and development of soybean is N. Large amounts of N are required because soybeans have a high protein content in seed, reaching 35-40%. Similar to other legumes, the source of N include the atmosphere and fertilization (Głowacka et al. 2023). Fertilization with N significantly affects plant height, number of pods per plant, and seed weight per plant. As stated by Zhang et al. (2024b), 40% to 52% of the total N absorption by soybeans comes from symbiotic N fixation, while the rest is nitrate absorbed from soil. Therefore, when the total N supply does not meet soybean needs, the plant will remobilize N accumulated in leaf to seed. This reduces photosynthesis and limits yield potential. The increase in seed yield due to N application can be attributed to the number of pods per plant and the number of seeds per pod.

**Table 1.** The intensity of sunlight (lux) under oil palm stands produced in a lifespan of 4 years

| Treatment | Research plot | Oil palm | Research plot | Oil palm |
|---|---|---|---|---|
| | Standard | | Modification | |
| Block I | 15.750 | 9.115 | 54.000 | 38.250 |
| Block II | 22.810 | 17.485 | 48.500 | 40.000 |
| Block III | 22.500 | 20.000 | 55.500 | 45.500 |
| Average | 20.353 | 15.533 | 52.667 | 41.250 |
| Percentage | 28% | 21% | 72% | 57% |

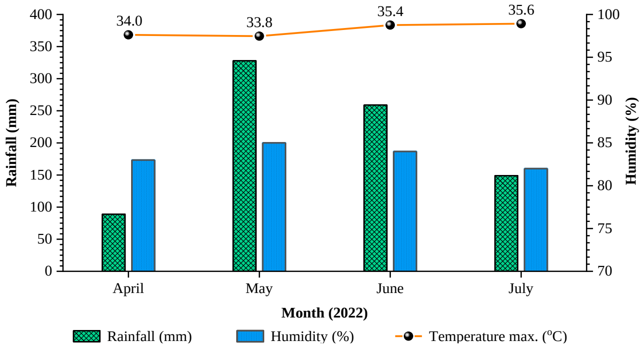


**Figure 4.** Four months of average rainfall, average air temperature, and rainy days in Percut Sei Tuan (North Sumatra, Indonesia) from April to July 2022

**Table 2.** Average soil nutrient analysis at the research location

| Soil nutrients | Treatment | Depth 0-20 cm | | Depth 20-40 cm | |
|---|---|---|---|---|---|
| | | Standard | Modification | Standard | Modification |
| pH | $J_1$ | 5.01 (S) | 5.09 (S) | 4.98 (S) | 5.09 (S) |
| | $J_2$ | 4.92 (S) | 4.91 (S) | 4.97 (S) | 5.00 (S) |
| | Ms | 4.91 (S) | 5.11 (S) | 4.96 (S) | 5.09 (S) |
| | Average | 4.95 (S) | 5.03 (S) | 4.97 (S) | 5.06 (S) |
| Nitrogen (N) | $J_1$ | 0.06 (Vl) | 0.21 (S) | 0.04 (Vl) | 0.15 (L) |
| | $J_2$ | 0.06 (Vl) | 0.23 (S) | 0.03 (Vl) | 0.17 (L) |
| | Ms | 0.09 (Vl) | 0.24 (S) | 0.04 (Vl) | 0.24 (M) |
| | Average | 0.07 (Vl) | 0.23 (S) | 0.04 (Vl) | 0.19 (L) |
| Phosphorus (P) | $J_1$ | 0.29 (Vh) | 0.27 (Vh) | 0.27 (Vh) | 0.25 (Vh) |
| | $J_2$ | 0.25 (Vh) | 0.28 (Vh) | 0.22 (Vh) | 0.27 (Vh) |
| | Ms | 0.37 (Vh) | 0.30 (Vh) | 0.31 (Vh) | 0.28 (Vh) |
| | Average | 0.30 (Vh) | 0.29 (Vh) | 0.27 (Vh) | 0.26 (Vh) |
| Potassium (K) | $J_1$ | 0.11 (Vh) | 0.11 (Vh) | 0.12 (Vh) | 0.10 (Vh) |
| | $J_2$ | 0.11 (Vh) | 0.10 (Vh) | 0.13 (Vh) | 0.11 (Vh) |
| | Mk | 0.12 (Vh) | 0.12 (Vh) | 0.12 (Vh) | 0.12 (Vh) |
| | Average | 0.11 (Vh) | 0.11 (Vh) | 0.12 (Vh) | 0.11 (Vh) |
| Carbon (C) | $J_1$ | 0.03 (Vl) | 0.05 (Vl) | 0.04 (Vl) | 0.04 (Vl) |
| | $J_2$ | 0.06 (L) | 0.04 (Vl) | 0.11 (M) | 0.04 (Vl) |
| | Ms | 0.03 (Vl) | 0.03 (Vl) | 0.03 (Vl) | 0.04 (Vl) |
| | Average | 0.04 (Vl) | 0.04 (Vl) | 0.06 (L) | 0.04 (Vl) |

Note: $J_1$: Standard oil palm planting distance; $J_2$: Engineered oil palm planting distance; Ms: Soybean monoculture; S: Sour; Vl: Very low; L: Low; M: Medium; Vh: Very high

**Table 3.** Analysis of soybean growth variance in an integrated system with oil palm planting distance engineering

| Treatment | Notation | Plant height 4 mst (cm) | Plant height at harvest (cm) | Number of productive branches | Flowering age (day) | Harvest age (day) |
|---|---|---|---|---|---|---|
| Planting system | J | | | | | |
| Standard | $J_1$ | 53.21±8.52 a | 132.68±7.61 a | 1.86±0.46 b | 29.19±1.36 b | 77.10±1.29 b |
| Modification | $J_2$ | **35.33±5.76 b** | **77.50±5.98 b** | **3.94±0.93 a** | **39.93±0.73 a** | **80.39±1.62 a** |
| Planting distance | T | | | | | |
| 30 cm × 20 cm | $T_1$ | 44.67±12.17 a | 105.91±29.12 a | 2.94±1.46 a | 34.70±5.61 a | 78.34±2.02 a |
| 35 cm × 25 cm | $T_2$ | 44.18±12.05 a | 104.69±30.16 a | 2.94±1.19 a | 34.59±5.86 a | 78.33±1.89 a |
| 40 cm × 15 cm | $T_3$ | 44.27±9.97 a | 103.64±29.06 a | 2.83±1.45 a | 34.55±5.53 a | 78.92±2.36 a |
| 40 cm × 20 cm | $T_4$ | 43.96±13.30 a | 106.12±30.20 a | 2.88±1.14 a | 34.39±5.87 a | 79.38±2.60 a |
| Soybean varieties | V | | | | | |
| Dena 1 | $V_1$ | **41.89±9.20 b** | 107.20±30.46 a | 3.11±1.32 a | 34.74±5.34 a | 78.66±2.14 a |
| Grobogan | $V_2$ | 46.65±13.27 a | **102.98±27.31 b** | **2.69±1.22 b** | 34.38±5.84 a | 78.83±2.32 a |
| ANOVA | df | | | | | |
| J | 1 | $62.74^{**}$ | $798.67^{**}$ | $109.02^{**}$ | $54.64^{**}$ | $57.21^{**}$ |
| T | 3 | $0.02^{ns}$ | $0.35^{ns}$ | $0.07^{ns}$ | $0.03^{ns}$ | $1.36^{ns}$ |
| V | 1 | $4.45^{*}$ | $4.65^{*}$ | $4.47^{*}$ | $0.04^{ns}$ | $0.16^{ns}$ |
| J × T | 3 | $0.02^{ns}$ | $0.04^{ns}$ | $1.07^{ns}$ | $0.05^{ns}$ | $0.18^{ns}$ |
| J × V | 1 | $1.77^{ns}$ | $3.44^{ns}$ | $2.33^{ns}$ | $0.12^{ns}$ | $0.40^{ns}$ |
| T × V | 3 | $0.33^{ns}$ | $0.70^{ns}$ | $0.18^{ns}$ | $0.09^{ns}$ | $0.20^{ns}$ |
| J × T × V | 3 | $0.68^{ns}$ | $0.87^{ns}$ | $0.11^{ns}$ | $0.12^{ns}$ | $0.27^{ns}$ |

Note: Numbers followed by different letters in the same column and group are significantly different by Tukey's test at the 0.05 level: least significant difference at $p<0.05$, means followed by the same letter in a column are not significantly different by least significant difference at $p<0.05$; ns: non-significant; *: $p<0.05$; **: $p<0.01$; data are means±Standard Errors (SE) of three replications

Adequate fertilization will optimize the growth and production of soybeans with intercropping on oil palm plantations (Monzon et al. 2023; Hendrawan and Musshoff 2024). Phosphate plays a role in cell growth, root formation, and development of root hairs. Photosynthates are translocated to the pods, thereby facilitating rapid filling and shortening harvest age. Potassium fertilizer plays a role in the formation of protein and fat, strengthening roots, leaves, flowers, and fruits to withstand drought and disease.

### Soybean growth in integrated system

Plant height at the age of 4 weeks and 8 weeks and harvest in the standard oil palm planting distance treatment were 53.21 cm, 108.47 cm, and 132.68 cm, respectively (Table 3). This was significantly different from the modified oil palm planting distance, which was 35.33 cm, 58.48 cm, and 77.50 cm, but the soybean planting distance was not significantly different in all observed parameters. Plant height for Dena 1 was 41.89 cm, 84.66 cm, and

107.20 cm, respectively, significantly different from Grobogan, which was 46.65 cm, 82.29 cm, and 102.98 cm.

**Soybean production in an integrated system**

Grobogan soybean variety crown and stem in the standard oil palm planting distance treatment were weaker than those planted in the modified and monoculture treatment. This can be attributed to the adaptation process, which causes changes in the spatial structure of the crown as well as the morphology and physiology of the stem in the intercropping system. On the other hand, the stem of Dena 1 soybean, including shade tolerant, was clearly stronger than the intolerant Grobogan soybean variety in terms of external morphology, internal structure, and physiological characteristics. The results showed that shade-tolerant soybeans increased the capture of light energy and photosynthesis at different canopy levels to promote the development of stem morphology and physiology, leading to a rise in productivity in the integrated system. Shade reduces light intensity, thereby limiting plant height, length of stem segments, leaf area per plant, as well as stem diameter (Kou et al. 2024; Yan et al. 2024). Significant yield reductions were caused by shade at the full pod-filling stage. Plant height, stem diameter, and dry weight were directly correlated to the influence of shade (Yang et al. 2023; Islam et al. 2024; Yan et al. 2024).

Table 4 shows the difference in soybean production per plot of 993.55 g: The modified oil palm planting distance system has a very significant effect on the standard oil palm planting distance of 202.40. This is following Table 1 which shows a positive correlation between sufficient light intensity (above 40,000 lux) and increased soybean production. When light intensity decreases below the optimal range, soybean yields will also decrease, especially in intercropping conditions with oil palm shade plants.

**Chlorophyll and anatomical structure of soybean integrated system**

Light intensity influenced soybean growth and production characteristics, specifically in the standard planting distance treatment. This is because oil palm leaf block 72% to 79% of sunlight, thereby suppressing growth. Plants experience etiolation as well as a reduced number of branches and pods, which leads to decreased seed yields per plant and plot. The modified oil palm distance treatment had the highest production of 993.55 g per-plot, which was significantly different from the standard system, at 202.40 g. Furthermore, Dena 1 produced a production per-plot of 692.90 g, which was significantly different from Grobogan, at 503.04 g. The decrease in seed yield for the standard oil palm planting distance treatment of 9 × 9 m was caused by insufficient light, which limited plant metabolic processes. This led to a reduction in the amount of photosynthate supplied to the generative organs, thereby reducing soybean seed yields (Raza et al. 2023).

Figure 5 shows three research locations that are significantly affected by planting distance and soybean variety. The amount of leaf chlorophyll in the modified and monoculture systems was not significantly different. The planting distance for Dena 1 with $T_2$ (35 cm × 25 cm) and $T_3$ (40 cm × 15 cm) was more than the standard. According to previous reports, Dena 1 soybean plants are tolerant to shade and can regulate leaf in line with the direction and intensity of light. In shaded conditions, plants direct chloroplasts to gather near the epidermis layer, resulting in leaf color becoming greener. Adaptation to shaded conditions is determined by the ability of plants to photosynthesize, usually in low-light conditions. Generally, solar radiation affects the chloroplast which tends to gather on the side of the cell wall closest and farthest from radiation. This condition causes leaf to appear green because the chloroplasts clump on the surface (Mawarni et al. 2019). However, in this research, the green color of leaf did not significantly affect the level of shade, variety, and combination. This is supported by the research of Zheng et al. (2022), stating that the integrated planting model affects the physiological process of plants related to photosynthesis. Environmental factors determine the efficiency of the absorption and transmission of light energy during the photosynthesis process. Based on the results, the standard oil palm planting distance treatment had a lower amount of leaf chlorophyll compared to the modified and monoculture.

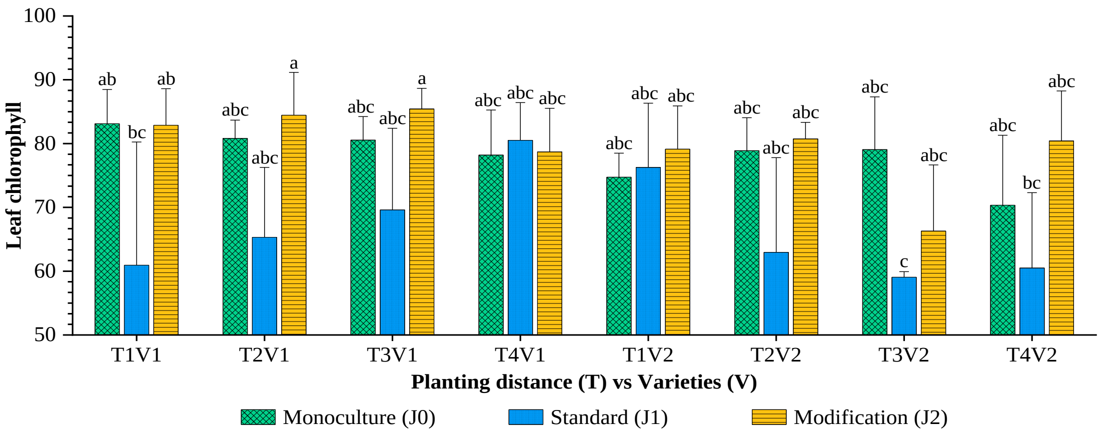


**Figure 5.** The average of leaf chlorophyll from two varieties (Dena 1 and Grobogan) among soybean planting distance under the different planting patterns

**Table 4.** Analysis of soybean production yield variance in an integrated system with the engineering of 4-year-old oil palm planting distance

| Treatment | Notation | Number of seeds per planting | Seed weight per plant (g) | Weight 100 seeds (g) | Production per-plot (g) |
|---|---|---|---|---|---|
| Planting system | J | | | | |
| Standard | $J_1$ | 18.54±6.89 b | 2.41±0.94 b | 13.23±2.95 b | 202.40±69.21 b |
| Modification | $J_2$ | **66.22±28.22 a** | **11.49±4.64 a** | **18.29±2.82 a** | **993.55±461.23 a** |
| Planting distance | T | | | | |
| 30 cm × 20 cm | $T_1$ | 39.70±30.24 a | 6.85±6.33 a | 15.10±4.93 a | 685.08±632.78 a |
| 35 cm × 25 cm | $T_2$ | 46.87 ±37.16 a | 7.22±5.53 a | 15.49±3.69 a | 498.18±381.66 a |
| 40 cm × 15 cm | $T_3$ | 45.39 ±36.58 a | 7.16±6.32 a | 15.33±2.67 a | 716.00±632.40 a |
| 40 cm × 20 cm | $T_4$ | 37.54 ±23.37 a | 6.57±5.08 a | 17.11±3.88 a | 492.63±381.02 a |
| Soybean varieties | V | | | | |
| Dena 1 | $V_1$ | **51.44 ±36.08 a** | **8.04±6.20 a** | 14.69±4.13 b | **692.90±564.44 a** |
| Grobogan | $V_2$ | 33.32±23.60 b | 5.86±4.95 b | **16.83±3.26 a** | 503.04±454.63 b |
| ANOVA | df | | | | |
| J | 1 | $88.05^{**}$ | $107.07^{**}$ | $43.83^{**}$ | $100.50^{**}$ |
| T | 3 | $0.77^{ns}$ | $0.12^{ns}$ | $1.35^{ns}$ | $2.28^{ns}$ |
| V | 1 | $12.72^{**}$ | $6.13^{*}$ | $7.36^{*}$ | $5.79^{*}$ |
| J × T | 3 | $0.72^{ns}$ | $0.31^{ns}$ | $1.30^{ns}$ | $2.06^{ns}$ |
| J × V | 1 | $7.59^{**}$ | $6.02^{*}$ | $4.75^{*}$ | $5.66^{*}$ |
| T × V | 3 | $0.51^{ns}$ | $0.28^{ns}$ | $0.12^{ns}$ | $0.42^{ns}$ |
| J × T × V | 3 | $0.86^{ns}$ | $0.65^{ns}$ | $0.16^{ns}$ | $0.59^{ns}$ |

Note: Numbers followed by different letters in the same column and group are significantly different by Tukey's test at the 0.05 level: least significant difference at p<0.05, means followed by the same letter in a column are not significantly different by least significant difference at p<0.05; ns: not significant; *: p<0.05; **: p<0.01; data are means±Standard Errors (SE) of three replications

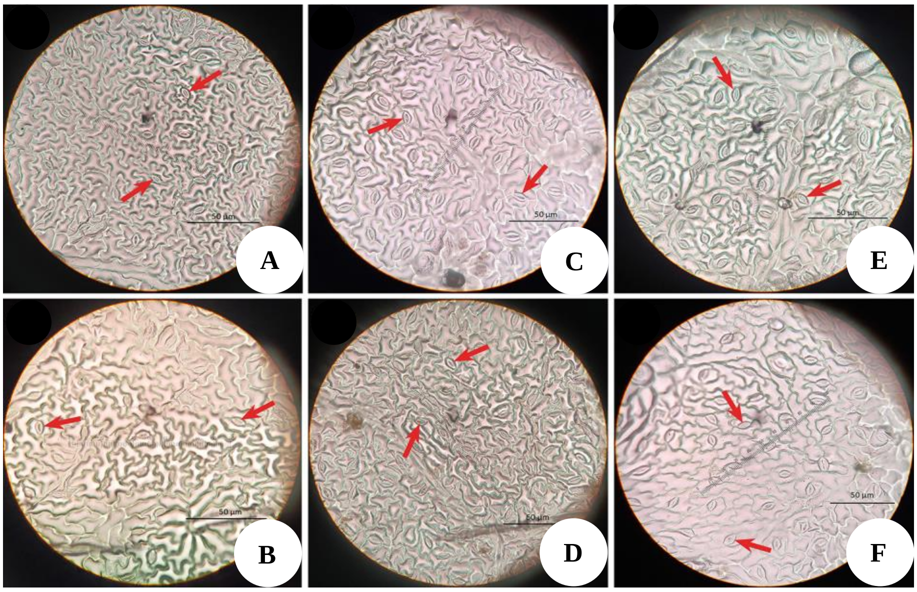


**Figure 6.** Leaf stomata of Dena 1 ($V_1$) and Grobogan ($V_2$) plants with 400x magnification. Standard oil palm planting distance: A. $J_1V_1$; B. $J_1V_2$. Modified oil palm planting distance: C. $J_2V_1$; D. $J_2V_2$. Soybean monoculture (M) planting system: E. $MV_1$; F. $MV_2$

The number of stomata on leaf without shade or monoculture was greater than with shade treatment. The difference could be attributed to environmental factors, specifically low light intensity and air humidity. The number of stomata for Dena 1 and Grobogan was 28 and 27, respectively. This proved that soybean plants with a low light intensity of 28% caused a decrease in the number of stomata. Dena 1 is more tolerant to shade and adapts quickly to lack of light than Grobogan. This is indicated by the number of stomata planted with standard and modified oil palm distance systems (Figure 6). According to Chen et al. (2022), the length of stomatal holes, the shape and size of the epidermis cells, as well as the development of leaf size are influenced by sunlight. Sakoda et al. (2019) further stated that light density affects the progress of photosynthesis and stomatal function in soybean plants due to the entry of carbon dioxide ($CO_2$) from the through small pores found on the surface of leaf. The greater the number of stomata, the higher the amount of $CO_2$ absorbed in leaf, thereby supporting the photosynthesis process.

Soybean plants with sufficient light intensity have a more efficient photosynthesis process by allowing more $CO_2$ to enter leaf. However, in low-light conditions, photosynthesis is not efficient. Soybean plants in high-humidity environments tend to have reduced water evaporation from leaf surface, with a small number of stomata (Hernandez et al. 2023). As stated by Bertolino et al. (2019), the number of stomata is also influenced by environmental factors, including changes in temperature and light intensity, atmospheric $CO_2$ concentration, air humidity, and soil water content. Therefore, the number of stomata in plants is the result of adaptation to environmental conditions. Soybean plants regulate the number of stomata to optimize the photosynthesis process while minimizing water loss, depending on the light and humidity conditions in oil palm plantation areas.

As shown in Figure 7, leaf thickness for soybean planted in the standard, modified, monoculture oil palm distance system, Dena 1 and Grobogan was 142.762 µm ($J_1V_1$), 106.644 µm ($J_1V_2$), 187.402 µm ($J_2V_1$), 211.355 µm ($J_2V_2$), 194.858 µm ($MV_1$), and 196.992 µm ($MV_2$), respectively. This research proved that Dena 1 and Grobogan experienced a decrease in leaf thickness compared to soybean plants planted in the modified and monoculture systems. The difference is mainly due to changes in leaf (Wen et al. 2020a; Li et al. 2024).

Compared to leaf in the modified oil palm distance and normal light, plants under shade showed a decrease in thickness of palisade and sponge tissues with significantly increased cell gaps. According to Fan et al. (2019), shade conditions increase the efficiency of light capture by photosystem II (PSII) in soybean leaf but reduce the transmission capacity of PSII to photosystem II (PSI). Photosynthesis also decreased when soybean plants were shaded.

Changes in leaf anatomy are among various efforts to increase light capture. The lowest leaf thickness was caused by the low light received, thereby reducing the rate of photosynthesis (Mawarni et al. 2019).

The cortex thickness of root in the standard, modified, monoculture treatment, as well as Dena 1 and Grobogan, was 1136.804 µm ($J_1V_1$), 1031.085 µm ($J_1V_2$), 1323.764 µm ($J_2V_1$), 1428.154 µm ($J_2V_2$), 1620.026 µm ($MV_1$), and 1709.373 µm ($MV_2$), respectively (Figure 8). Root anatomy results show a decrease in cortex thickness in the standard distance system with a light intensity of 28%. At the same time, the modification and monoculture treatment experienced an increase in the cortex. According to Wen et al. (2020b), the cortex is a basic tissue that functions to store photosynthesis results, water, and minerals.

The decrease in cortex thickness in the standard system treatment is a tolerance mechanism for Dena 1 and Grobogan to shorten the distance of water transportation into the stele and xylem. Furthermore, the increase in the number of cells in the cortex enhances plant tolerance to drought stress. Compared to monocropping, intercropping soybeans with oil palm can significantly increase productivity due to the optimal utilization of available natural resources such as light, water, soil, and nutrients. Oil palm and soybean plants have different root architecture and depth; specifically, oil palms usually have deeper root systems, while soybeans have shorter taproots. This reduces competition for water and nutrients because absorption varies at different soil layer depths according to root length (Nasar et al. 2024).

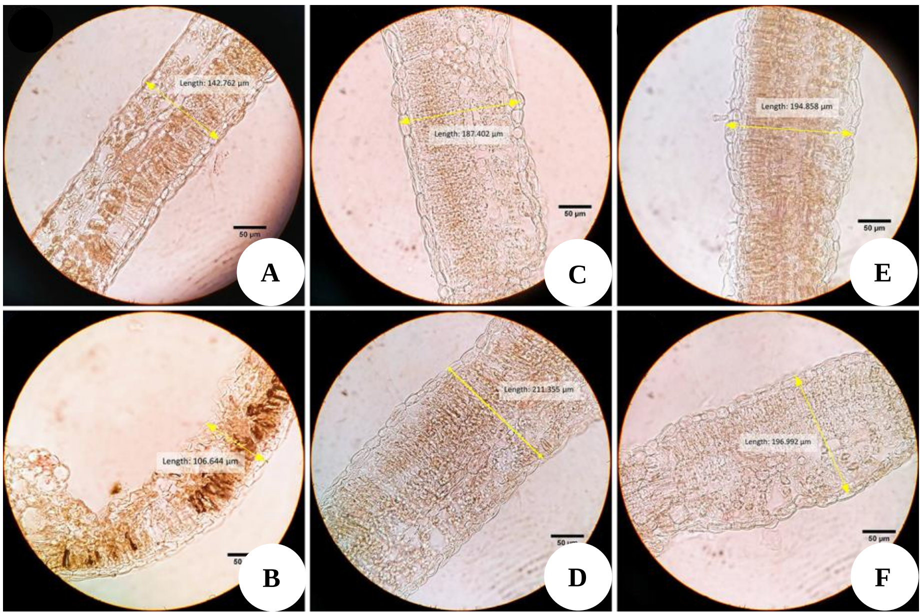


**Figure 7.** The thickness of soybean plant leaf in Dena 1 ($V_1$) and Grobogan ($V_2$) with 400x magnification. Standard oil palm planting distance: A. $J_1V_1$; B. $J_1V_2$. Modified oil palm planting distance: C. $J_2V_1$; D. $J_2V_2$. Soybean monoculture (M) planting system: E. $MV_1$; F. $MV_2$.

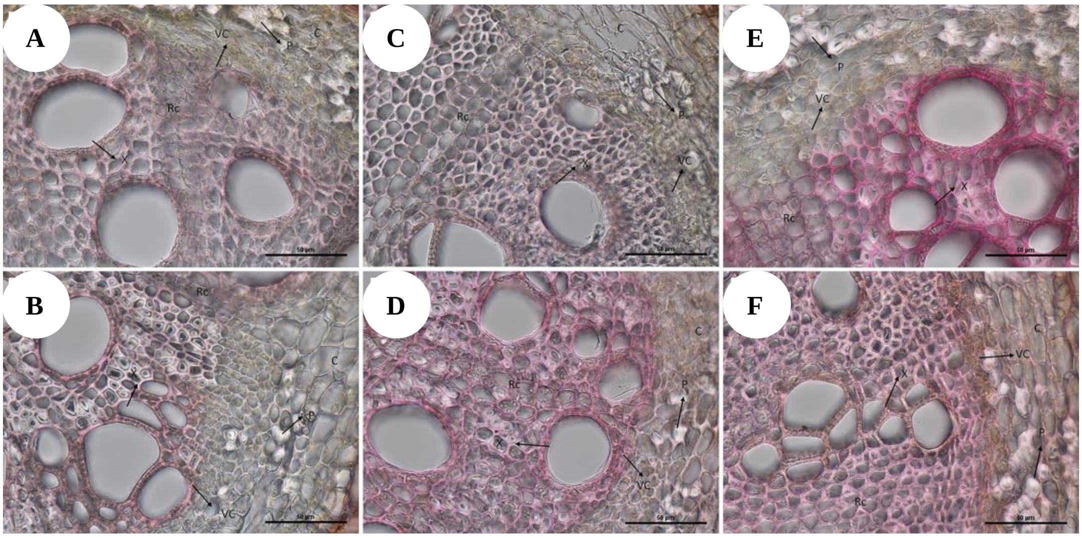


**Figure 8.** Soybean plant root Dena 1 ($V_1$). and Grobogan ($V_2$) with 400x magnification. Standard oil palm planting distance: A. $J_1V_1$; B. $J_1V_2$. Modified oil palm planting distance: C. $J_2V_1$; D. $J_2V_2$. Soybean monoculture planting system: E. $MV_1$; F. $MV_2$

**Table 5.** LER of soybean for the application of integrated cultivation in oil palm plantations

| Treatment | Productivity (kg per-plot) | LER |
|---|---|---|
| Dena 1 Standard | 0.203 | 0.18 |
| Grobogan Standard | 0.201 | 0.20 |
| Dena 1 Modification | 1.182 | 1.06 |
| Grobogan Modification | 0.805 | 0.81 |
| Dena 1 Monoculture | 1.112 | - |
| Grobogan Monoculture | 0.998 | - |

**Land Equivalent Ratio (LER)**

Integration of soybean with oil palm for land use efficiency was demonstrated in LER model which was used to estimate the influence of competition and yield benefits from the land use side (Table 5).

The modified oil palm planting distance using Dena 1 provided productivity of 1,182 kg per-plot with LER value of 1.06 compared to Grobogan with values of 0.805 kg per-plot and 0.81, respectively. LER results in the standard planting system for Dena 1 and Grobogan were 0.18 and 0.20.

The integration of soybean oil palm cultivation showed an LER value of 1, indicating that the integration of oil palm modification + Dena 1 was very feasible. Ladha et al. (2022) stated land productivity can be increased by selecting the right combination of plants and planting systems as well as the existence of a beneficial relationship or mutualistic symbiosis. The advantages of the integration system are closely related to N requirements for the main crops, which are met by soybeans through the ability to fix N from the air. Moreover, soybean plants are tolerant to shade and can live under oil palm stands.

**Production and income of soybean and oil palm**

Fresh Fruit Bunches (FFB) produced from standard oil palm planting distance treatment, as well as Dena 1 and Grobogan, were 3 740.80 kg FFB $ha^{-1}$ per-3 months, 65.09 kg $ha^{-1}$, and 64.44 kg $ha^{-1}$, respectively (Table 6). The average income was IDR 7.481.600 for oil palm yields per-soybean planting season. Dena 1 and Grobogan accounted for an average income of IDR 781.080 and IDR 773.280, respectively.

Integration of soybean oil palm with modified oil palm planting distance engineering treatment produced 2065.91 kg FFB $ha^{-1}$, while Dena 1 and Grobogan produced 737.83 kg $ha^{-1}$ and 502.15 kg $ha^{-1}$, respectively. The average income was IDR 4.131.820 for oil palm yields per-soybean planting season, with both varieties amounting to IDR 8.853.960 and IDR 6.025.800, respectively (Table 7). This income can be a solution for sustainable farmers in addition to more optimal oil palm health and growth. Therefore, the planting distance engineering treatment method for soybeans has significant potential in the long term. Integration reduces dependence on soybean imports and increases food security. The positive impacts include increased agricultural productivity, reduced environmental impacts, and support for farmer welfare. Collaborative efforts, including government support, training, market diversification, and close monitoring, are essential to optimize the potential of the system (Junaidi et al. 2024).

Based on the results, Dena 1 can increase income at modified oil palm planting distances. This is because the sunlight needed by soybeans is not reduced due to the relatively wide planting distance. According to Harsono and Harnowo (2022), soybean cultivation in oil palm plantations can be applied for up to 3 years before plants are produced and has the potential to increase productivity by around 2 t/ha, by using shade-tolerant varieties, such as Dena 1.

The economic feasibility analysis results show the efficiency obtained by oil palm farmers in soybean production through the Return Cost Ratio. For Dena 1, the R/C ratio of 1.79 indicates that soybean-oil palm integration farming business with planting distance engineering is feasible or profitable because additional income is greater than costs.

**Table 6.** Production and income of soybean-oil palm integration

| Planting pattern | Production 3 months | Income (IDR) |
|---|---|---|
| Integration of soybean-oil palm standard oil palm planting distance | | |
| Production (140 trees $ha^{-1}$) | 3740.80 kg FFB $ha^{-1}$ | 7.481.600 |
| Soybean production var. Dena 1 | 65.09 kg $ha^{-1}$ | 781.080 |
| Soybean production var. Grobogan | 64.44 kg $ha^{-1}$ | 773.280 |
| Soybean-oil palm integration modification oil palm planting distance | | |
| Oil palm production (77 trees $ha^{-1}$) | 2065.91 kg FFB $ha^{-1}$ | 4.131.820 |
| Soybean production var. Dena 1 | 737.83 kg $ha^{-1}$ | 8.853.960 |
| Soybean production var. Grobogan | 502.15 kg $ha^{-1}$ | 6.025.800 |
| Monoculture of soybean var. Dena 1 | 1482.72 kg $ha^{-1}$ | 17.792.640 |
| Monoculture of soybean var. Grobogan | 1330.80 kg $ha^{-1}$ | 15.969.600 |
| Oil palm monoculture (140 trees $ha^{-1}$) | 3764.60 kg FFB $ha^{-1}$ | 7.529.200 |

**Table 7.** Analysis of soybean-Oil palm integration income

| Planting pattern | Income (IDR) | Cost (IDR) | Profit (IDR) | R/C |
|---|---|---|---|---|
| Integration of JT standard oil palm var. Dena 1 | 8.262.680 | 8.187.641 | 75.039 | 1.01 |
| Integration of JT standard oil palm var. Grobogan | 8.254.880 | 8.187.641 | 67.239 | 1.01 |
| Integration of JT modification oil palm var. Dena 1 | 12.985.780 | 7.265.470 | 5.720.310 | 1.79 |
| Integration of JT modification oil palm var. Grobogan | 10.157.620 | 7.265.470 | 2.892.150 | 1.40 |
| Monoculture of soybean var. Dena 1 | 17.792.640 | 10.881.700 | 6.910.940 | 1.64 |
| Monoculture of soybean var. Grobogan | 15.969.600 | 10.881.700 | 5.087.900 | 1.47 |
| Monoculture of oil palm | 7.529.200 | 5.235.361 | 2.293.839 | 1.44 |

Grobogan R/C ratio of 1.40 (>1.00) indicates soybean-oil palm integrated farming with a planting distance engineering system is feasible or profitable. By using this planting pattern, farmers can harvest soybeans outside the season without reducing the yield of fresh oil palm fruit bunches (Cheng et al. 2022). The limited sunlight received affected the morphological and physiological characteristics of soybeans with an intercropping planting system. Using the integration system, oil palm plantations can serve as polyculture crops. Thinning oil palm planting distances reduces pest and disease attacks, thereby increasing production.

In conclusion, the integration of soybeans in oil palm plantations with a planting distance of 9 m × 15.6 m produced the highest productivity in Dena 1. This led to higher land use efficiency. The treatment also produced higher profit compared to monoculture and improved environmental conditions, specifically N nutrient. This shows that simultaneous cultivation with the engineering of oil palm planting distance can give intercropping advantages, specifically with shade-tolerant soybean variety Dena 1. Light limitation in soybeans occurred when intercropped with oil palms, and N content decreased in shade treatment due to the reduced N2 fixation rate. The limitation related to the low light level of oil palm-based intercropping system was modified by thinning plant spacing. The long-term success of this system depends on other factors, such as modified nutrient status and increased hydrological inputs under oil palm trees. However, further in-depth research is needed to provide theoretical guidance for the cultivation of soybean plants using an oil palm distance engineering model that can adapt to changes in light environments.

## ACKNOWLEDGEMENTS

The authors thank the Board of Commissioners and Management PT. LPP Agro Nusantara, Indonesia and Rector of *Institut Teknologi Sawit Indonesia* (ITSI) who give support and facilitate leadership and staff of the *Badan Meteorologi Klimatologi dan Geofisika*, Sampali, North Sumatera, Indonesia for their assistance in providing vital meteorological data and analysis.

## REFERENCES

Bertolino LT, Caine RS, Gray JE. 2019. Impact of stomatal density and morphology on water-use efficiency in a changing world. Front Plant Sci 10: 225. DOI: 10.3389/fpls.2019.00225.

BPS. 2024. Indonesian Soybean Imports 2017-2023. https://www.bps.go.id/id/statistics-table/1/MjAxNSMx/impor-kedelai-menurut-negara-asal-utama--2017-2023.html. [Indonesian]

Chen J, Gao J, Wang Q, Tan X, Li S, Chen P, Yong T, Wang X, Wu Y, Yang F, Yang W. 2022. Blue-light-dependent stomatal density and specific leaf weight coordinate to promote gas exchange of soybean leaves. Agriculture 13 (1): 119. DOI: 10.3390/agriculture13010119.

Cheng B, Wang L, Liu R, Wang W, Yu R, Zhou T, Ahmad I, Raza A, Jiang S, Xu M, Liu C, Yu L, Wang W, Jing S, Liu W, Yang W. 2022. Shade-tolerant soybean reduces yield loss by regulating its canopy structure and stem characteristics in the maize–soybean strip intercropping system. Front Plant Sci 13: 848893. DOI: 10.3389/fpls.2022.848893.

Enesi RO, Dyck M, Chang S, Thilakarathna MS, Fan X, Strelkov S, Gorim LY. 2023. Liming remediates soil acidity and improves crop yield and profitability - a meta-analysis. Front Agron 5: 1194896. DOI: 10.3389/fagro.2023.1194896.

Fan Y, Chen J, Wang Z, Tan T, Li S, Li J, Wang B, Zhang J, Cheng Y, Wu X, Yang W, Yang F. 2019. Soybean (*Glycine max* L. Merr.) seedlings response to shading: Leaf structure, photosynthesis and proteomic analysis. BMC Plant Biol 19 (1): 34. DOI: 10.1186/s12870-019-1633-1.

Głowacka A, Jariene E, Flis-Olszewska E, Kiełtyka-Dadasiewicz A. 2023. The effect of nitrogen and sulphur application on soybean productivity traits in temperate climates conditions. Agronomy 13 (3): 780. DOI: 10.3390/agronomy13030780.

Guo B, Sun L, Jiang S, Ren H, Sun R, Wei Z, Hong H, Luan X, Wang J, Wang X, Xu D, Li W, Guo C, Qiu L-J. 2022. Soybean genetic resources contributing to sustainable protein production. Theor Appl Genet 135 (11): 4095-4121. DOI: 10.1007/s00122-022-04222-9.

Harsono A, Elisabeth DAA, Muzaiyanah S, Rianto SA. 2020. Soybean-maize intercropping feasibility under drought-prone area in East Java, Indonesia. Biodiversitas 21 (8): 3744-3754. DOI: 10.13057/biodiv/d210842.

Harsono A, Harnowo D. 2022. The potential of area under young oil palm plantation on tidal swamps for soybean development. IOP Conf Ser: Earth Environ Sci 974: 012099. DOI: 10.1088/1755-1315/974/1/012099.

Hendrawan D, Musshoff O. 2024. Smallholders' preferred attributes in a subsidy program for replanting overaged oil palm plantations in Indonesia. Ecol Econ 224: 108278. DOI: 10.1016/j.ecolecon.2024.108278.

Hernandez JO, Manese LGA, Lalog HL, Herradura VJV, Abasolo WP, Maldia LSJ. 2023. Growth and morpho-stomatal response of Kenaf (*Hibiscus cannabinus*) to varying water, light, and soil conditions. J Sylva Lestari 11 (3): 345-359. DOI: 10.23960/jsl.v11i3.757.

Hood ASC, Advento AD, Stone J, Fayle TM, Fairnie ALM, Waters HS, Foster WA, Snaddon JL, Sudharto P, Caliman J-P, Naim M, Turner EC. 2020. Removing understory vegetation in oil palm agroforestry reduces ground-foraging ant abundance but not species richness. Basic Appl Ecol 48: 26-36. DOI: 10.1016/j.baae.2020.07.002.

Islam MS, Ghimire A, Lay L, Khan W, Lee J-D, Song Q, Jo H, Kim Y. 2024. Identification of quantitative trait loci controlling root morphological traits in an interspecific soybean population using 2D imagery data. Intl J Mol Sci 25 (9): 4687. DOI: 10.3390/ijms25094687.

Junaidi A, Mashar AZ, Basrowi B, Muharomah DR, Situmorang JW, Lukas A, Asgar A, Herlina L, Manalu LP, Payung L. 2024. Enhancing sustainable soybean production in Indonesia: Evaluating the environmental and economic benefits of MIGO technology for integrated supply chain sustainability. Uncertain Supply Chain Manag 12: 221-234. DOI: 10.5267/j.uscm.2023.10.003.

Khalid MHB, Raza MA, Yu HQ, Sun FA, Zhang YY, Lu FZ, Si L, Iqbal N, Khan I, Fu FL, Li WC. 2019. Effect of shade treatments on morphology, photosynthetic and chlorophyll fluorescence characteristics of soybeans (*Glycine max* L. Merr.). Appl Ecol Environ Res 17 (2): 2551-2569. DOI: 10.15666/aeer/1702_25512569.

Kou H, Liao Z, Zhang H, Lai Z, Liu Y, Kong H, Li Z, Zhang F, Fan J. 2024. Grain yield, water-land productivity and economic profit responses to row configuration in maize-soybean strip intercropping systems under drip fertigation in arid northwest China. Agric Water Manag 297: 108817. DOI: 10.1016/j.agwat.2024.108817.

Krisdiana R, Prasetiaswati N, Sutrisno I, Rozi F, Harsono A, Mejaya MJ. 2021. Financial feasibility and competitiveness levels of soybean varieties in rice-based cropping system of Indonesia. Sustainability 13 (15): 8334. DOI: 10.3390/su13158334.

Ladha JK, Peoples MB, Reddy PM, Biswas JC, Bennett A, Jat ML, Krupnik TJ. 2022. Biological nitrogen fixation and prospects for ecological intensification in cereal-based cropping systems. Field Crops Res 283: 108541. DOI: 10.1016/j.fcr.2022.108541.

Li Z, Lyu X, Li H, Tu Q, Zhao T, Liu J, Liu B. 2024. The mechanism of low blue light-induced leaf senescence mediated by GmCRY1s in soybean. Nat Commun 15 (1): 798. DOI: 10.1038/s41467-024-45086-5.

Mawarni L, Nisa TC, Napitupulu JA, Karyudi K. 2019. Determination of leaf status of soybean varieties on shading: Chlorophyll and chloroplast. Biodiversitas 20 (2): 615-620. DOI: 10.13057/biodiv/d200243.

Monzon JP, Lim YL, Tenorio FA et al. 2023. Agronomy explains large yield gaps in smallholder oil palm fields. Agric Syst 210: 103689. DOI: 10.1016/j.agsy.2023.103689.

Nasar J, Ahmad M, Gitari H, Tang L, Chen Y, Zhou X-B. 2024. Maize/soybean intercropping increases nutrient uptake, crop yield and modifies soil physio-chemical characteristics and enzymatic activities in the subtropical humid region based in Southwest China. BMC Plant Biol 24 (1): 434. DOI: 10.1186/s12870-024-05061-0.

Noor HF. 2007. Ekonomi Manajerial. PT. Raja Grafindo Persada. Jakarta. [Indonesian]

Pelech EA, Evers JB, Pederson TL, Drag DW, Fu P, Bernacchi CJ. 2023. Leaf, plant, to canopy: A mechanistic study on aboveground plasticity and plant density within a maize-soybean intercrop system for the Midwest, USA. Plant Cell Environ 46 (2): 405-421. DOI: 10.1111/pce.14487.

Purwanto E, Santoso H, Jelsma I, Widayati A, Nugroho HYSH, van Noordwijk M. 2020. Agroforestry as policy option for forest-zone oil palm production in Indonesia. Land 9 (12): 531. DOI: 10.3390/land9120531.

Raza A, Asghar MA, Javed HH, Ullah A, Cheng B, Xu M, Wang W, Liu C, Rahman A, Iqbal T, Saleem K, Liu W, Yang W. 2023. Optimum nitrogen improved stem breaking resistance of intercropped soybean by modifying the stem anatomical structure and lignin metabolism. Plant Physiol Biochem 199: 107720. DOI: 10.1016/j.plaphy.2023.107720.

Sakoda K, Watanabe T, Sukemura S, Kobayashi S, Nagasaki Y, Tanaka Y, Shiraiwa T. 2019. Genetic diversity in stomatal density among soybeans elucidated using high-throughput technique based on an algorithm for object detection. Sci Rep 9: 7610. DOI: 10.1038/s41598-019-44127-0.

Saragih WS, Purba E, Lisnawita L, Basyuni M. 2021. The Fourier transform infrared spectroscopy from *Diplazium esculentum* and *Rivina humilis* analysis to reveals the existence of necessary components in oil palm plantations of *Ganoderma boninense* control. Biodiversitas 22 (9): 3645-3651. DOI: 10.13057/biodiv/d220902.

Staniak M, Szpunar-Krok E, Kocira A. 2023. Responses of soybean to selected abiotic stresses-Photoperiod, temperature and water. Agriculture 13 (1): 146. DOI: 10.3390/agriculture13010146.

Suwandi S, Alesia M, Munandar RP, Fadli R, Suparman S, Irsan C, Muslim A. 2024. The suppression of *Ganoderma boninense* on oil palm under mixed planting with taro plants. Biodiversitas 25 (3): 1143-1150. DOI: 10.13057/biodiv/d250329.

Vogel JT, Liu W, Olhoft P, Crafts-Brandner SJ, Pennycooke JC, Christiansen N. 2021. Soybean yield formation physiology - A foundation for precision breeding based improvement. Front Plant Sci 12: 719706. DOI: 10.3389/fpls.2021.719706.

Wagino, Rauf A, Hanum C, Rahmanta. 2021. Karakteristik agronomi dan hasil varietas kedelai toleran naungan (*Glycine max* (L.) Merrill) di bawah tegakan kelapa sawit menghasilkan. Proceeding seminar nasional perhimpunan agronomi Indonesia pertanian berkelanjutan untuk mendukung swasembada hasil pertanian nasional dan kesejahteraan petani. Jatinangor, 03 November 2021. [Indonesian]

Wang H, Zhang Z, Li F, Hu L, Xiao T, Zhao Y, Yang M. 2024. The effects of dietary fermented soybean residue on the growth, antioxidant capacity, digestive enzyme activities, and microbial compositions of the intestine in Furong Crucian Carp (Furong Carp♀ × Red Crucian Carp♂). Fishes 9 (4): 138. DOI: 10.3390/fishes9040138.

Wen B-X, Hussain S, Yang J-Y, Wang S, Zhang Y, Qin S-S, Xu M, Yang W-Y, Liu W-G. 2020a. Rejuvenating soybean (*Glycine max* L.) growth and development through slight shading stress. J Integr Agric 19 (10): 2439-2450. DOI: 10.1016/S2095-3119(20)63159-8.

Wen B, Zhang Y, Hussain S, Wang S, Zhang X, Yang J, Xu M, Qin S, Yang W, Liu W. 2020b. Slight shading stress at seedling stage does not reduce lignin biosynthesis or affect lodging resistance of soybean stems. Agronomy 10 (4): 544. DOI: 10.3390/agronomy10040544.

Yan C, Shan F, Wang C, Lyu X, Wu Y, Yan S, Ma C. 2024. Positive correlation of lodging resistance and soybean yield under the influence of uniconazole. Agronomy 14 (4): 754. DOI: 10.3390/agronomy14040754.

Yang L, Liu J, Li N, Pei Y, Peng J, Wang Z. 2023. An integrated strategy coordinating endogenous and exogenous approaches to alleviate crop lodging. Plant Stress 9: 100197. DOI: 10.1016/j.stress.2023.100197.

Zhang J, Shiraiwa T, Katsube-Tanaka T. 2023. Evaluation of the susceptibility to green stem disorder in soybeans [*Glycine max* (L.) Merr.] with vegetative storage protein accumulation. Plant Prod Sci 26 (2): 131-142. DOI: 10.1080/1343943X.2023.2196026.

Zhang L, Feng Y, Zhao Z, Baoyin B, Cui Z, Wang H, Li Q, Cui J. 2024a. Macrogenomics-Based analysis of the effects of intercropped soybean photosynthetic characteristics and nitrogen-Assimilating enzyme activities on yield at different nitrogen levels. Microorganisms 12 (6): 1220. DOI: 10.3390/microorganisms12061220.

Zheng H, Wang J, Cui Y, Guan Z, Yang L, Tang Q, Sun Y, Yang H, Wen X, Mei N, Chen X, Gu Y. 2022. Effects of row spacing and planting pattern on photosynthesis, chlorophyll fluorescence, and related enzyme activities of maize ear leaf in maize–soybean intercropping. Agronomy 12 (10): 2503. DOI: 10.3390/agronomy12102503.

Zhang T, Liu Y, Ge S, Peng P, Tang H, Wang J. 2024b. Sugarcane/soybean intercropping with reduced nitrogen addition enhances residue-derived labile soil organic carbon and microbial network complexity in the soil during straw decomposition. J Integr Agric 2024. DOI: 10.1016/j.jia.2024.02.020.