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Performance of edamame soybean (*Glycine max* (L.) merril) under different intercropping systems for sustainable agriculture

Y Hartini, P W Titisari*

Department of Agrotechnology, Universitas Islam Riau, Jalan Kaharudin Nasution No 113, Pekanbaru-Riau 28284, Indonesia

*Email: pw.titisari@agr.uir.ac.id

Abstract. Intercropping offers a sustainable strategy to increase land productivity and optimize resource use in agricultural systems. This study evaluated the growth performance and yield of edamame soybean (*Glycine max* (L.) Merrill) under five cropping models: monoculture, single row, double row zig-zag, double row vertical, and box intercropping with maize. The experiment employed a completely randomized design with three replications, and observations included plant height, leaf area, flowering time, pod number, fresh pod weight, chlorophyll content, light intensity, and land equivalent ratio (LER). Results showed that the double row vertical model (S3) produced the highest plant height (23.1 cm), leaf area (65.8 cm²), pod number (24.93), and fresh pod weight (70.03 g per plant). The monoculture system (S0) recorded the highest chlorophyll content (42.13 SPAD), while the zig-zag model (S2) resulted in the earliest flowering (29 days after sowing). Although the box intercropping model (S4) achieved the highest LER (1.96), it reduced individual plant performance due to excessive shading. These findings suggest that the double row vertical intercropping system provides an optimal balance between light distribution, plant development, and land-use efficiency, making it a promising approach for sustainable edamame–maize production in tropical environments.

1. Introduction

Edamame (*Glycine max* (L.) Merrill) is a tropical legume originally cultivated in Japan and widely consumed as a green vegetable soybean due to its high content of proteins, isoflavones, antioxidants, and other essential nutrients [1,2]. In Indonesia, edamame is considered a strategic food crop, yet its cultivation remains limited in scale and productivity. According to the Ministry of Agriculture (2020), Indonesia was only able to fulfill 13.58% of Japan's frozen edamame demand (6.790 tons), while domestic consumption reached approximately 75.000 tons annually [3]. This highlights the need to boost national edamame production to meet both export and local market demands.

One of the major constraints affecting edamame productivity in Indonesia is the decline in soil fertility due to continuous monoculture practices. Repetitive cultivation of the same crop can lead to nutrient depletion, reduced biodiversity, and soil degradation [4,5]. Intercropping has been proposed as a sustainable alternative that improves land-use efficiency, enhances light and water use, and restores soil health through ecological and biological interactions [6].



Several intercropping models—such as single row, double row (zig-zag or vertical), and box systems—have been explored in other crops [7–10]. However, studies focusing on maize-edamame intercropping are still scarce, despite their complementary growth characteristics. Edamame, a C3 plant with low canopy and high light sensitivity, can benefit from the partial shading provided by maize, a tall C4 plant with high light tolerance [11]. Such intercropping systems may reduce excessive photorespiration in edamame and support more balanced microclimatic conditions for growth. Therefore, this study aimed to evaluate the performance of edamame soybeans under various maize intercropping systems. By identifying the most effective planting model, this research contributes to sustainable agricultural development and provides practical insights for optimizing land productivity in tropical farming systems.

2. Materials and method

2.1. Study site and duration

The experiment was conducted at the Experimental Farm of the Faculty of Agriculture, Universitas Islam Riau, Indonesia. The study took place over three months, from January to March 2025.

2.2. Materials and tools

The biological materials used in this study were edamame soybean seeds (Biomax 1 variety) and maize seeds (Bonanza F1 variety). Additional materials included chicken manure, organic NPK fertilizer, and botanical pesticides. The tools used in the field included a hoe, rake, watering can, measuring tape, SPAD chlorophyll meter, analytical balance, digital camera, and writing instruments.

2.3. Experimental design

A completely randomized design (CRD) was employed, consisting of five treatments with three replications, resulting in 15 experimental units. Each unit comprised eight edamame plants, with four designated as sample plants, yielding a total of 120 plants. The treatments were defined as follows:

S0: Monoculture (8 edamame plants)

S1: Single row intercropping (8 edamame + 8 maize plants)

S2: Double row zig-zag intercropping (8 edamame + 8 maize plants)

S3: Double row vertical intercropping (8 edamame + 4 maize plants)

S4: Box system intercropping (8 edamame + 16 maize plants)

All treatments were arranged and spaced according to the respective intercropping models illustrated in Figure 1.

2.4. Planting procedure

Seeds were sown directly in the field at a depth of 2 cm, one seed per hole, and covered with soil. Both edamame and maize were planted simultaneously. Harvesting of edamame was conducted 65 days after sowing (DAS) when the pods were fully filled and green.

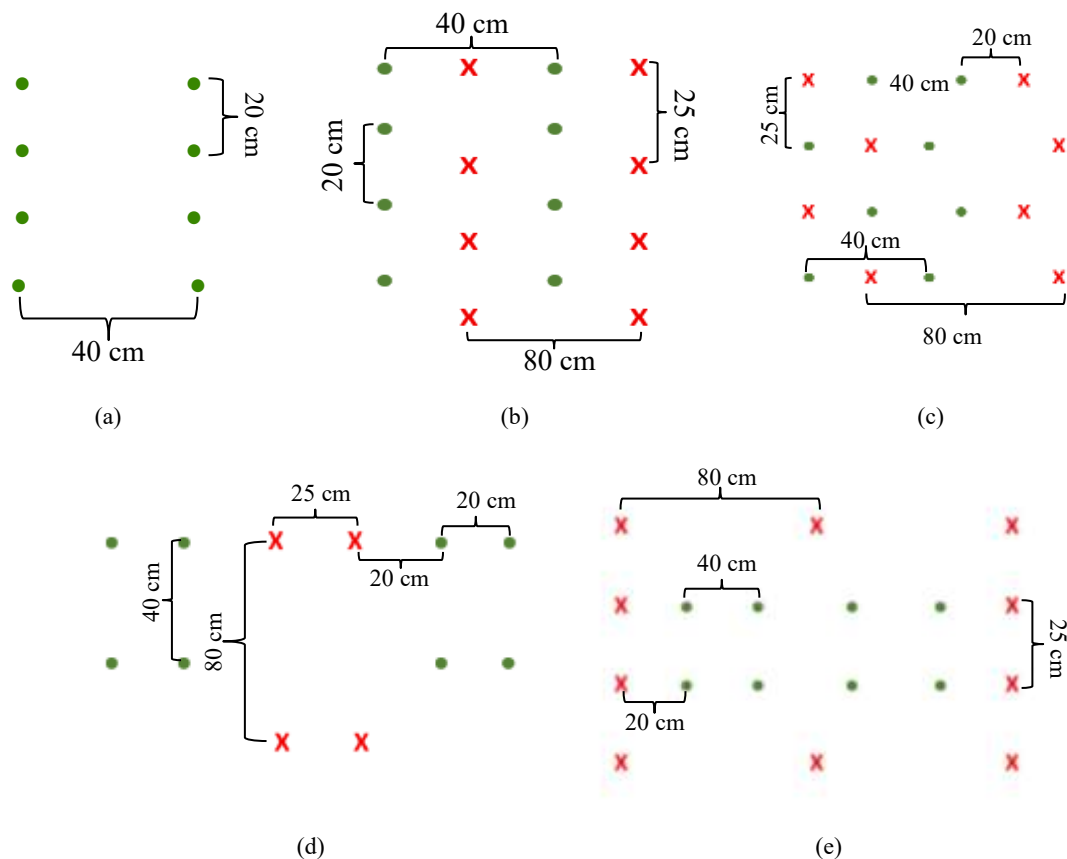


Figure 1. Nutmeg samples model tumpangsari. (a) Monoculture; (b) Single Row; (c) Double Row Zig-zag; (d) Double Row Vertical; (e) Box System. (X = Corn; ● = Edamame)

2.5. Observed parameters and measurements

The parameters observed included plant height, flowering time, leaf area, harvest time, number of pods per plant, fresh pod weight, leaf chlorophyll content, light intensity, and land equivalent ratio (LER). Leaf area was measured by photographing the third leaf and analyzing it using ImageJ software. Chlorophyll content was measured using a SPAD chlorophyll meter on the third leaf. Light intensity was recorded above and below the edamame canopy using a lux meter, and interception percentage was calculated using Equation (1):

$$I = \frac{a - b}{b} \quad (1)$$

Where:

I = light interception (%)

a = radiation above the canopy

b = radiation below the canopy

Land Equivalent Ratio (LER) was calculated using Equation (2):

$$LER = \frac{Y_{ab}}{Y_{aa}} + \frac{Y_{ba}}{Y_{bb}} \quad (2)$$

Where:

Yab = yield of edamame in intercropping

Yaa = yield of edamame in monoculture

Yba = yield of maize in intercropping

Ybb = yield of maize in monoculture

An $LER > 1$ indicates an advantage of intercropping, $LER < 1$ indicates a disadvantage, and $LER = 1$ indicates no advantage.

2.6. Data analysis

All data were statistically analyzed using analysis of variance (ANOVA). If a significant effect was observed ($F\text{-value} > F\text{-table}$), means were compared using the Honestly Significant Difference (HSD) test at the 5% level.

3. Results and discussion

3.1. Plant height (cm)

Table 1 and Figure 2 show the plant height of edamame under different intercropping models. The highest plant height was observed in the S3 (double row vertical) treatment at 23.1 cm, which was significantly different from other treatments except S4. The lowest height was recorded in the S1 (single row) model at 16.16 cm. This difference may be attributed to shading effects from maize, which induced stem elongation in edamame due to increased auxin distribution under low-light conditions [12,13]. These findings are consistent with previous studies reporting that leguminous crops grown under partial shading often exhibit taller plants than those in full sunlight, due to reduced photoinhibition and enhanced nitrogen cycling in shaded environments [14–16].

Table 1. Average height of edamame plants 28 days after planting in various intercropping models (cm).

Treatment	Average
S0	16.73 bc
S1	16.16 c
S2	17.63 bc
S3	23.1 a
S4	20.8 ab
CV= 2.61%	HSD=4.43

Description: The numbers in the columns followed by the same lower case letter are not significantly different according to the 5% HSD test.

According to [13], environmental factors such as water availability, sunlight, and humidity play critical roles in plant growth. Plants grown in shaded conditions exhibit cell elongation and increased height, as auxin activity is less inhibited by light. Conversely, plants in unshaded environments experience reduced elongation due to suppressed auxin activity [14].

These results align with previous research indicating that peanut and soybean plants in intercropping systems often exhibit taller growth than in monoculture systems due to moderated light intensity and improved soil conditions [17–19].

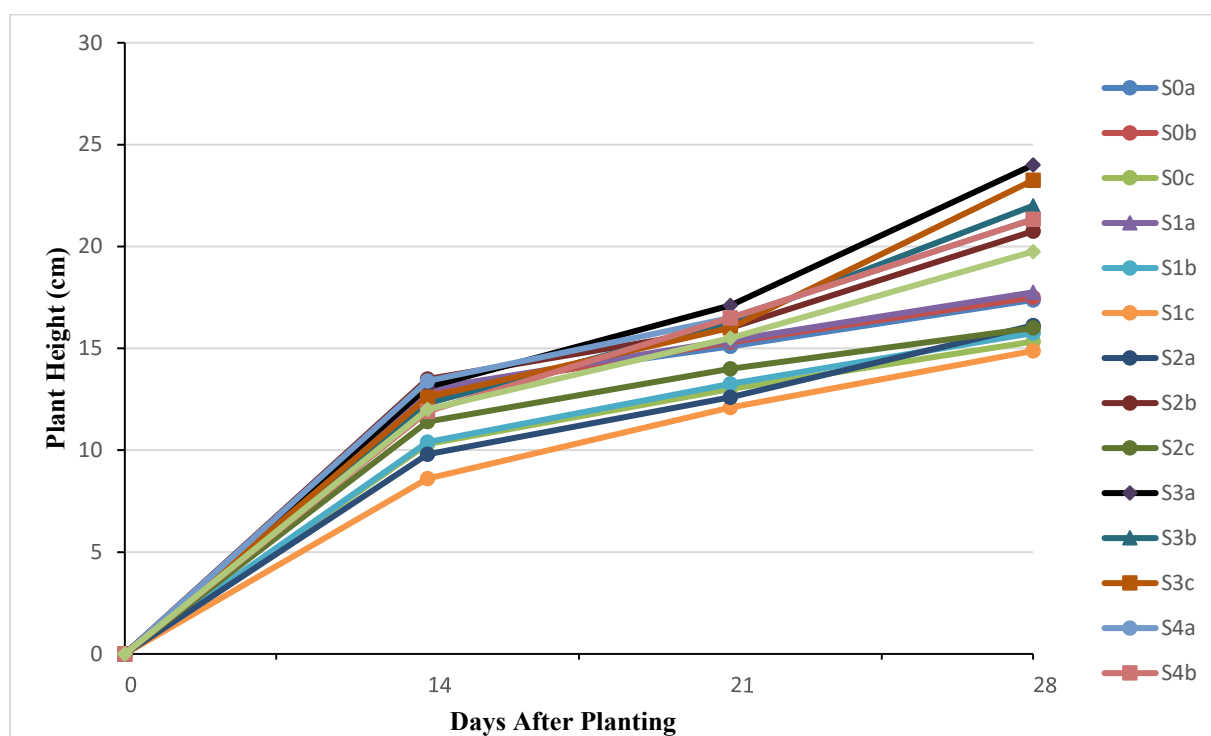


Figure 2. Height of edamame soybean plants in various intercropping models

3.2. Flowering time (days after sowing)

The average flowering time for each treatment is shown in Table 2. The shortest time to flowering was recorded in treatment S2 (double row zig-zag intercropping), which flowered at 29.03 DAS, significantly earlier than the other treatments. This early flowering response may result from partial shading provided by maize, which can increase air temperature and create favorable conditions for floral induction. [20] suggested that shading and genotype interaction can accelerate flowering in soybean.

Table 2. Average flowering age of edamame in various intercropping models.

Treatment	Average
S0	33.36 c
S1	31.93 b
S2	29.03 a
S3	31.93 b
S4	32.60 bc
CV= 0.23%	HSD=1.30

Description: The numbers in the columns followed by the same lower case letter are not significantly different according to the 5% HSD test.

Similar results were reported by , who observed flowering initiation between 28–36 DAS in soybean under intercropping models. The presence of maize modifies the light and temperature environment around the edamame plants, which in turn influences the vegetative and reproductive transitions.

Appropriate plant spacing also plays an important role. Narrow spacing may lead to nutrient competition, while optimal spacing supports better light interception and nutrient availability. The results of this study confirm that the double row zig-zag model improves edamame flowering by providing a balanced microenvironment.

3.3. Leaf area (cm^2)

The leaf area of edamame plants under various intercropping systems is presented in Table 3. The largest leaf area was recorded in treatment S3 (double row vertical) at 65.8 cm^2 , followed by S0 (monoculture, 47.9 cm^2) and S1 (single row, 41.3 cm^2). The smallest leaf areas were observed in treatments S2 and S4.

Table 3. Average leaf area of edamame plants 35 days after planting in various intercropping models.

Treatment	Average
S0	47.9 ab (1.7) a
S1	41.3 ab (1.5) a
S2	16.5 b (1.16) a
S3	65.8 a (1.8) a
S4	16 b (1.2) a
CV= 0.06 %	HSD= 0.70

Description: The numbers in the columns followed by the same lower case letter are not significantly different according to the 5% HSD test. Data () is a data transformed log x.

Leaf expansion is a physiological adaptation of plants to optimize light absorption under shaded conditions. Moderate shading typically stimulates leaf expansion to increase the photosynthetically active surface area [16]. However, excessive shading—as observed in the box system (S4)—can limit light penetration and reduce leaf development[21–23].

These findings are in line with previous research showing that soybean leaf morphology is significantly influenced by light availability, genotype, and environmental interactions [24–26]. Shaded leguminous crops often display narrower leaf blades or smaller surface areas due to reduced photosynthetic activity [12,14,27,28]. The results of this study confirm that the double row vertical model provides a favorable balance of shading and light exposure, promoting wider leaf development in edamame. Conversely, the dense maize population in the box system restricted light penetration and thus limited leaf expansion. This condition emphasizes the critical role of intercropping design in determining canopy architecture and light distribution.

3.4. Harvest time (days after sowing)

Table 4 summarizes the average harvest time of edamame under different planting models. All treatments—monoculture and the four intercropping systems—showed similar results, with harvest time averaging around 64 days after sowing (DAS).

Table 4. Average harvest age of edamame in various intercropping models.

Treatment	Average
S0	64.60
S1	64.10
S2	64.35
S3	64.70
S4	64.36

There were no statistically significant differences among treatments regarding the harvest period. This similarity indicates that shading from maize had minimal influence on the generative phase duration.

of edamame. Factors contributing to this include the use of a shade-tolerant variety, moderate light conditions during the growth cycle, and favorable microclimatic support for photosynthesis continuity.

These findings align with previous research [22,23], which reported similar harvest times between monoculture and intercropping systems in soybeans. In this study, slight delays in maturity may be attributed to overcast weather and high rainfall intensity during the experimental period, potentially affecting light interception and flowering synchrony [24].

3.5. Number of pods per plant (pods)

The number of pods per plant under different intercropping models is presented in Table 5. The highest pod number was observed in treatment S3 (double row vertical), with an average of 24.93 pods per plant. This was significantly higher than in S1 and S4. The lowest number of pods was found in S4 (box system), with only 11.6 pods per plant.

Table 5. Average number of pods per edamame plant in various intercropping models.

Treatment	Average
S0	20.76 ab
S1	15.26 bc
S2	19.26 ab
S3	24.93 a
S4	11.6 c
CV=4.80%	HSD= 5.89

Description: The numbers in the columns followed by the same lower case letter are not significantly different according to the 5% HSD test.

Pod number is a critical yield determinant in edamame and is directly influenced by flowering success and photosynthetic activity. The higher number of pods in S3 suggests that this model provides an optimal microenvironment that supports flower formation and retention. Maize spacing in this treatment likely offered partial shade without excessively blocking light, enhancing the edamame's reproductive development.

Shading has been shown to influence flowering and pod development in legumes [25,26]. Moderate shading from maize can reduce light stress and water loss, maintaining suitable conditions for flower fertilization and pod set. Conversely, in the S4 treatment, the dense maize canopy may have caused excessive shading, leading to reduced flower formation or increased flower abortion, and consequently, fewer pods [29,30]. Furthermore, pod number is influenced by plant competition for light, nutrients, and water. The reduced pod count in the box system likely resulted from high plant density, which limited resource availability per plant. Previous studies have shown that excessive interspecific competition in intercropping systems can negatively affect pod set in legumes [31,32].

3.6. Fresh pod weight per plant (g)

Table 6 presents the average fresh pod weight of edamame under various intercropping models. The highest fresh pod weight was recorded in S3 (double row vertical) at 70.03 g per plant, followed by S0 (monoculture) at 52.56 g. The lowest pod weight occurred in S4 (box system), with only 21.1 g per plant.

Table 6. Average fresh pod weight per edamame plant in various intercropping models.

Treatment	Average
S0	52.56 b
S1	29.46 cd
S2	37.23 c
S3	70.03 a
S4	21.1 d
CV= 13.0%	HSD= 9.69

Description: The numbers in the columns followed by the same lower case letter are not significantly different according to the 5% HSD test.

Fresh pod weight is a composite yield parameter influenced by pod number, pod size, and overall plant health. The superior performance of S3 in both pod number and weight underscores the effectiveness of the double row vertical model in supporting edamame productivity. This system likely allowed for optimal light distribution, reduced heat stress, and balanced competition between maize and edamame[30]. The lower yields observed in S4 may be attributed to excessive shading and increased plant competition, which limit photosynthetic efficiency and biomass accumulation [33–35]. Additionally, the dense maize canopy in the box system may have created an unfavorable microclimate, reducing the assimilate partitioning to pods and limiting sink development.

These findings are consistent with previous studies demonstrating that intercropping patterns with adequate spacing can increase resource-use efficiency and yield stability [34,35]. Moreover, the results affirm the potential of the double row vertical model to enhance both pod quantity and quality in sustainable edamame-maize intercropping systems.

3.7. Leaf chlorophyll content (Chlorophyll/mm²)

Table 7 shows the average chlorophyll content in edamame leaves under different intercropping models. The highest value was observed in the monoculture system (S0) with 42.13 chlorophyll/mm², followed by S1 and S2. The lowest chlorophyll content was recorded in the box system (S4) at 36.73 chlorophyll/mm².

Table 7. Average chlorophyll content of edamame plant leaves in various intercropping models.

Treatment	Average
S0	42.13 a
S1	39.30 b
S2	38.20 b
S3	37.13 b
S4	36.73 b
CV= 0.9%	HSD= 2.65

Description: The numbers in the columns followed by the same lower case letter are not significantly different according to the 5% HSD test.

Chlorophyll is essential for photosynthesis and serves as a reliable indicator of plant health and nutrient status. The higher chlorophyll content in monoculture indicates better light absorption and photosynthetic capacity due to the absence of shading. In contrast, intercropped treatments experienced partial shading from maize, which limited light availability, thereby reducing chlorophyll synthesis [36–38].

These results align with studies suggesting that light intensity directly affects chlorophyll content in soybean leaves [42–44]. While shading can reduce photooxidative stress, excessive shade—as in the S4 treatment—may limit light-dependent chlorophyll production, reducing overall plant vigor. Moreover, lower chlorophyll levels in intercropping systems can also result in lighter green foliage, as observed

visually in shaded edamame plants. Such physiological responses are typical under low irradiance conditions and have implications for reduced photosynthetic efficiency and yield potential [24,36].

3.8. Light intensity (lux)

Table 8 presents the measured light intensity at the edamame canopy level across treatments. The highest light intensity was recorded in S0 (monoculture) at 0.75 lux, significantly higher than in S4 (box system), which showed the lowest value of 0.32 lux.

Table 8. Average Light Intensity of Edamame in Various Intercropping Models .

Treatment	Average
S0	0.75 a
S1	0.45 ab
S2	0.48 ab
S3	0.43 ab
S4	0.32 b
CV= 0.18%	HSD=0.36

Description: The numbers in the columns followed by the same lower case letter are not significantly different according to the 5% HSD test.

Light intensity is a critical environmental factor that drives photosynthesis, stomatal activity, and biomass accumulation. The lower light levels observed in S4 are attributed to the dense maize canopy, which reduced radiation penetration to the edamame plants. As a result, the photosynthetic capacity was constrained, leading to decreased growth and productivity. In contrast, S3 (double row vertical) and S2 (zig-zag) maintained intermediate light levels, which appear to support a favorable balance between shading and light transmission. Previous research confirms that moderate shade can optimize microclimatic conditions while minimizing water loss and photoinhibition [39–41].

The findings confirm that intercropping design and plant spacing play vital roles in controlling canopy light dynamics. Properly managed shade can reduce stress and enhance resource-use efficiency, but excessive shading—as seen in the box system—can be detrimental to understory crops like edamame [42].

3.9. Land equivalent ratio (LER)

The Land Equivalent Ratio (LER) values of the different intercropping treatments are presented in Table 9. The highest LER was recorded in the S4 treatment (box system) at 1.96, followed by S2 (1.61), S1 (1.53), and S3 (1.43).

Table 9. Average Land Equivalence Ratio of Edamame in Various Intercropping Models.

Treatment	Average
S1	1.53
S2	1.61
S3	1.43
S4	1.96

LER is an indicator of intercropping efficiency compared to monoculture systems. An LER greater than 1 signifies a yield advantage of intercropping. Despite lower individual yields in the S4 treatment, the overall land productivity was highest due to the high total output of both edamame and maize components.

These findings are consistent with earlier studies suggesting that even when one component yields less under intercropping, the total combined productivity can be higher, justifying the use of LER as a tool for evaluating intercropping performance [40,41,43]. However, it is important to note that higher LER in the S4 model may come at the cost of reduced edamame quality and individual yield parameters, as observed in previous sections. Therefore, while the box system shows high land-use efficiency, the double row vertical system (S3) may offer a more balanced outcome between yield quality and land productivity.

4. Conclusions

This study demonstrated that intercropping edamame soybean (*Glycine max* (L.) Merrill) with maize significantly influenced multiple growth and yield parameters. The double row vertical intercropping system (S3) produced the best outcomes in terms of plant height (23.1 cm), leaf area (65.8 cm²), pod number per plant (24.93), and fresh pod weight (70.03 g). The zig-zag model (S2) induced the earliest flowering (29 days after sowing), while the monoculture system (S0) resulted in the highest chlorophyll content (42.13 chlorophyll/mm²). Although no significant differences were observed in harvest time across treatments, the box system (S4) showed the highest land equivalent ratio (LER = 1.96), indicating maximum land-use efficiency. However, this model also demonstrated the lowest individual plant performance due to excessive shading. Overall, the double row vertical intercropping model offers a balanced approach by enhancing edamame yield without compromising plant health, making it a promising strategy for sustainable agriculture in tropical regions. Future studies are encouraged to assess long-term soil quality and economic viability of these intercropping models.

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