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Increasing Solar Radiation Use Efficiency (RUE) of Maize (*Zea mays* L.) through Arranging the Layout of Several Intercrop Plants

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Abstract**—** *Maize plants grown in monoculture system that often cannot utilize sunlight optimally. Intercropping methods with several C3 intercrops such as rice, soybeans, and bambara groundnuts are expected to enhance the solar radiation use efficiency (RUE) of maize plants. This study aims to improve the solar radiation use efficiency (RUE) of maize (Zea mays L.) through the arrangement of various intercrops layouts. The experiment was conducted from July to November 2021 at the Faculty of Agriculture Experimental Field, Jatimulyo, Malang, East Java. The experiment consisted of Split Plot Design (SPD) with Orthogonal Contrasts for control treatments. The main factor consisted of the type of companion crops, such as rice, soybeans, and bambara groundnuts, while the second factor was the companion crop layout, consisting of three level: one row, two rows, and three rows. The results showed that the intercropping pattern with two rows of soybeans produced the highest land equivalent ratio (LER) value of 1.38 compared to other treatments. Additionally, the intercropping system generally provided the highest interception and solar radiation use efficiency of 94.07% and 6.19%, respectively, where the companion crop treatments in one and two rows each yielded the highest RUE values of 6.88% and 6.43%. Based on the research conducted, it was concluded that the arrangement of intercrop plant layouts in the intercropping system can enhance solar radiation use efficiency (RUE) and offer potential optimization of space and resources in agricultural systems.*

Keywords**—** ***Radiation use efficiency, intercropping, intercrop patterns, intercrop plant, maize.***

I. INTRODUCTION

Autotroph plants utilize solar energy in the photosynthesis process to convert it into chemical energy. The efficiency of solar energy conversion into chemical energy is measured as the percentage of solar radiation energy converted into chemical energy (Lawlor, 2001). The solar radiation use efficiency (RUE) of C3 plants reaches up to 9.4%, whereas C4 plants can achieve up to 12.3%. This efficiency is influenced by genetic and environmental factors, including the selection of superior varieties and optimal cultivation systems. Inadequate cultivation systems, such as suboptimal plant population and the use of varieties that are unresponsive to radiation intensity, can reduce solar radiation use efficiency (Zhu et al., 2010).

Maize (Zea mays L.) is a C4 plant that is more efficient in using CO2 for photosynthesis. Generally, maize is grown in monoculture, which leads to suboptimal utilization of sunlight. Increasing the efficiency of solar radiation energy conversion can be achieved through intercropping methods. This method increases plant population, reduces unused sunlight, and optimizes the space between main crops (Sugito, 2009). Additional benefits of this method include improved soil fertility and reduced plant pests (Aisyah and Herlina, 2018).

The selection of plant species in intercropping systems is crucial because the solar radiation requirements vary among plants. For example, the solar radiation use efficiency of maize reaches 1.6 g MJ-1, higher than sorghum, rice, and wheat (Aznur, 2017). Specific plant species selection and optimal layout are also necessary to enhance RUE, as reported by Suryanto (2018), where intercropping between potatoes and kidney beans increased RUE by 1.84% compared to monoculture, which was only 1.24%. Increasing plant population in kidney bean intercropping with higher companion crop density also improved RUE by 12-36% compared to lower densities.

Efforts to increase RUE can be made by intercropping between C4 plants like maize and C3 plants such as upland rice, edamame soybeans, and bambara groundnuts. This combination utilizes the solar radiation intensity transmitted by the taller maize morphology to lower C3 plants like rice. Additionally, the intercropping pattern between non-legume C4 plants and leguminous C3 plants like soybeans and bambara groundnuts, which have shrub-like and low habitus, can provide complementary effects. These include utilizing the transmitted solar radiation from maize and the addition of nitrogen nutrients from Rhizobium bacteria fixation in the roots of soybeans and Bambara groundnuts.

Based on the above explanation, it is expected that intercropping between C4 and C3 plants can increase the efficiency of solar radiation energy conversion on maize fields. The aim of this experiment is to obtain information on the types of companion crops that can enhance interception efficiency and solar radiation use efficiency in different intercropping layout.

II. MATERIALS AND METHOD

2.1 Experimental Detail

The experiment was conducted from July to November 2021 at the Faculty of Agriculture Experimental Field in Jatimulyo, Malang, East Java. The experiment utilized a Split Plot Design (SPD) and Orthogonal Contrasts for control treatments. The treatments consisted of the type of companion crops as the first factor and the companion crop pattern as the second factor, with the following details:

K = Maize monoculture (control)

Main plots were the three types of companion crops among the maize plants, which included:

T1 = Upland rice

T2 = Edamame Soybeans

T3 = Bambara groundnuts

Subplots were the population of companion crops among the maize plants, consisting of three levels of companion crop patterns:

P1 = One row

P2 = Two rows

P3 = Three rows

The combination of the two treatment factors resulted in 9 treatment combinations with 1 control treatment and 3 replications, which is obtained the total of 30 experimental units.

The data were analyzed using combined analysis of variance (ANOVA) (F-test) at a 5% significance level to determine the effects of the treatments. If significant effects were found, the analysis was followed by the Honestly Significant Difference (HSD) test at a 5% significance level.

2.2 Field Experiment

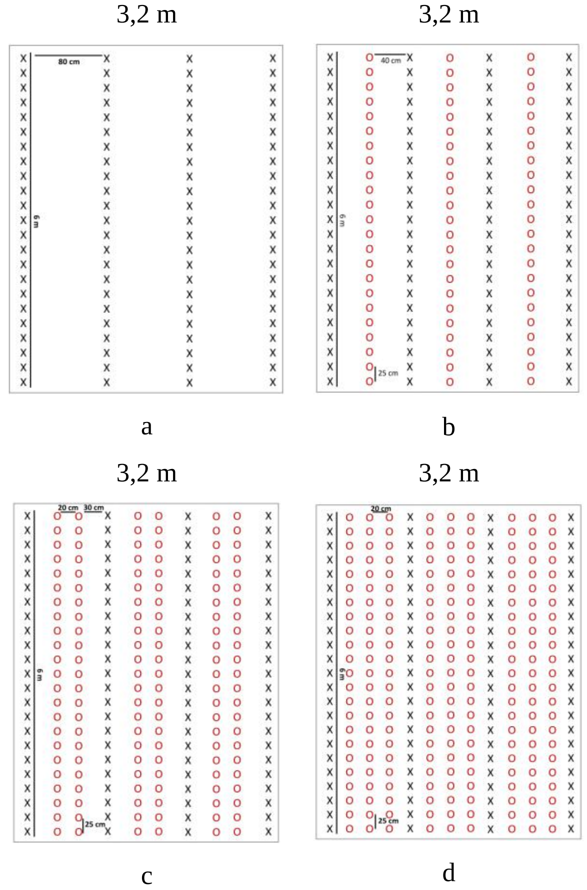

Fig.1: Layout of the number of intercrop plant rows (O) among maize plants (X): a. control (no intercrop), b. one row, c. two rows, d. three rows.

The experimental site was at an elevation of 450 meters above sea level, with an air temperature of 23°C - 25°C and regosol soil type. The annual rainfall was approximately 2447 mm.year^{-1}. Maize and companion crop seeds were planted using four planting layout methods according to the treatments. Maize was planted in monoculture (control) and intercropping systems as a main plant with a planting distance of 80 x 25 cm. Each companion crops were planted in planting holes prepared according to the following planting distances: one row at 80 cm x 25 cm; two rows at 20 cm x 25 cm and 60 cm x 25 cm; three rows at 20 cm x 25 cm, 20 cm x 25 cm, and 40 cm x 25 cm. The planting layout illustration presented in Figure 1.

The materials used in this experiment included BISI-18 maize seeds, Inpago 9 upland rice seeds, Edamame soybean seeds, Bambara groundnut seeds, urea fertilizer (46% N) at a dosage of 250 $kg.ha^{-1}$, and compound NPK fertilizer (15:15:15) at a dosage of 200 $kg.ha^{-1}$. Maintenance activities included weeding, replanting, watering, pest control, and fertilization. Daily solar radiation intensity data were obtained from the nearest climatology station (BMKG Karangploso, Malang, East Java), while daily solar radiation interception data were collected using a lux meter.

2.3 Observation

Plant observations included monitoring the maize growth observations, harvest observations, and solar radiation efficiency observations. The growth observation variables comprised plant height, number of leaves, leaf area, and leaf area index at 58 days after planting (DAP); total dry weight up to 72 DAP; and plant growth rate up to 58 DAP. Harvest observations included maize yield and land equivalent ratio (LER). The land equivalent ratio (LER), according to Guritno (2011), was used to determine land use efficiency in the intercropping pattern using the following formula:

$$\text{LER} = \frac{\text{Yi}}{\text{Yj}} + \frac{\text{Xi}}{\text{Xj}}$$

Explanation:

Yi: production of crop a in intercropping system a and b

Xi: production of crop b in intercropping system a and b

Yj: production of crop a in monoculture

Xj: production of crop b in monoculture

The solar radiation observations included interception efficiency at 58 days after planting (DAP) and radiation use efficiency at harvest. Interception efficiency (IE) indicates the percentage of solar radiation captured by the plant canopy (Sugito, 2009), which is calculated using the following equation:

$$\text{Ei} = \frac{\text{Ij} - \text{Il}}{\text{Ij}} \text{x } 100\%$$

Explanation:

Ij: Amount of solar radiation falling on a plant canopy

Il: Amount of radiation passing through the plant canopy

Radiation use efficiency (RUE) is the percentage of solar energy falling on the plant that can be converted into carbohydrate energy from photosynthesis, which is contained in the plants dry matter (Sugito, 2009). The equation for RUE according to Yoshida (1981) is as follows:

$$\text{RUE} = \frac{\Delta\text{W.K}}{\text{I.t.PAR}} \text{x}100\%$$

Explanation:

ΔW: Difference in plant dry weight (g) per m^2 over a given time period

K: Coefficient of heat combustion (4,000 cal g^{-1})

I: Daily solar radiation intensity (cal m^{-2} day^{-1})

t: A specific time period (days)

PAR: Photosynthetic Active Radiation (0.45)

III. RESULT & DISCUSSION

3.1 Growth Observation

Based on the analysis of variance results for the variables of plant height, number of leaves, leaf area, and leaf area index, there were no significant differences between the monoculture and intercropping treatment at 30-58 days after planting (DAP). The average plant height, number of leaves, leaf area, and leaf area index of maize plants due to the treatment of intercropping plant types and intercropping patterns at 58 DAP are presented in Table 1.

Observation results generally indicate that the variance analysis of each factor in the treatment of intercropping plant types and intercropping patterns did not significantly affect the height of maize plants from 30 to 58 DAP. However, the average height of maize plants under the treatment of intercropping plants and intercropping plant populations continued to increase up to 58 DAP.

Table 1. The Effect of Intercropping Plant Types and Intercropping Patterns on Several Growth Components.

Treatments	Plant Height ($cm.plant^{-1}$)	Number of Leaves ($sheet.plant^{-1}$)	Leaf Area ($cm^2.plant^{-1}$)	Leaf Area Index
Monoculture	201,00	11,33	5822,83	2,91
Intercropping	202,22	11,37	6173,87	3,09
Intercrop Plant Type				
Rice	193,72±18,41	11,39±0,93	6319,17±897,69	3,16±0,45
Soybean	205,94±14,68	11,11±0,65	6176,22±738,89	3,09±0,37
Bambara Groundnut	202,67±15,93	11,61±0,65	6026,22±968,54	3,01±0,48
LSD 5%	ns	ns	ns	ns
CV (%)	8,73	9,54	12,05	12,05
Intercropping Pattern				
One Row	208,39±13,88	11,67±0,79	6672,00±721,19	3,34±0,36
Two Rows	197,44±20,64	11,39±0,55	6154,00±941,60	3,08±0,47
Three Rows	196,50±13,47	11,06±0,85	5695,61±628,11	2,85±0,31
LSD 5%	ns	ns	ns	ns
CV (%)	5,02	6,32	13,11	13,11

Note: Values are based on the mean ± standard deviation; ns = not significantly different based on the 5% LSD test.

Total dry weight variable of maize plants based on analysis of variance indicate that there are differences between monoculture and intercropping treatments with intercropped plants on the total dry weight of maize plants at 72 DAP. In the intercropping treatments, there is an interaction between the type of intercropped plant and the intercropping pattern affecting the dry weight of maize plants at 58 and 72 DAP. The average dry weight of maize plants due to the interaction between the type of intercropped plant and the intercropping pattern is presented in Table 2.

Table 2. Total Dry Weight of Maize Plants Average Due to the Interaction of Intercropping Plant Types and Intercropping Patterns

Treatments	Total Dry Weight of Maize Plants ($g.plant^{-1}$)	
	58 DAP	72 DAP
Monoculture	258,01	324,33 A
Intercropping	252,79	425,18 B
Intercrop with Rice		
One Row	282,67 b	370,64 ab
Two Rows	311,78 b	446,59 abc
Three Rows	269,62 b	413,96 abc
Intercrop with Soybean		
One Row	244,09 ab	445,84 abc
Two Rows	255,99 b	441,48 abc
Three Rows	159,53 a	336,47 a
Intercrop with Bambara		
One Row	275,62 b	499,37 bc
Two Rows	229,97 ab	539,37 c

Three Rows	245,86 ab	332,91 a
LSD 5%	90,14	136,27
CV (%)	12,43	11,46

Note: Values followed by the same letter in the same column indicate no significant difference (uppercase letters for Orthogonal Contrast test and lowercase letters for 5% LSD test); DAP = Days After Planting.

The observations in Table 2 indicate that at 58 DAP, the dry weight of maize plants in the soybean intercropping treatment showed an increase of 60.47% in the two-row population compared to the three-row population, though there was no significant difference compared to the one-row population. At 72 DAP, the intercropping treatment with companion plants increased the dry weight of maize by 31.67% compared to the monoculture maize treatment. The total dry weight of maize in rice and soybean intercropping did not show significant differences among the intercropping patterns. The bambara groundnut intercropping treatment in the two-row and one-row populations did not show significant differences but resulted in a higher total maize dry weight of 62.02% and 50.00%, respectively, compared to the three-row population. Fewer plant populations and wider planting distances reduce competition among plants in terms of nutrient and water absorption. Kholid et al. (2023) stated that wider planting distances between soybeans and maize can reduce the level of competition in absorbing nutrients and light for the photosynthesis process. Xia et al. (2013) added that closer planting distances cause the roots of maize and legumes like soybeans to intermingle, leading to competition for utilizing the nitrogen fixation products from legume plants.

The results of variance analysis indicated that there were differences between monoculture maize treatments and intercropping with secondary crops in terms of maize growth rate at the ages of 30-44 days after planting (DAP) and 44-58 DAP. Additionally, among the intercropping treatments, there was no interaction between the type of secondary crop and the pattern of secondary crop planting at any observation age. The average growth rate of maize plants influenced by the type of secondary crop and the pattern of secondary crop planting is presented in Table 3.

Table 3. Growth Rate of Maize Plants Due to the Influence of Intercrop Plant Type and Intercropping Pattern.

Treatments	Maize Growth Rate (g.m^{-2}.day^{-1} plant^{-1}) at DAP	
	30-44	44-58
Monoculture	28,53 A	57,83
Intercropping	35,94 B	47,76
Intercrop Plant Type		
Rice	32,39 a	63,46 b
Soybean	36,83 ab	35,18 a
Bambara Groundnut	38,59 b	44,64 a
LSD 5%	4,83	11,69
CV (%)	8,16%	14,27%
Intercropping Pattern		
One Row	37,36	51,33 b
Two Rows	32,83	55,81 b
Three Rows	37,62	36,14 a
LSD 5%	ns	13,36
CV (%)	14,52%	22,78%

Note: Values followed by the same letter in the same column indicate no significant difference (uppercase letters for Orthogonal Contrast test and lowercase letters for 5% LSD test); DAP = Days After Planting; ns = not significantly different based on the 5% LSD test.

Maize growth rate at the age of 30-44 days after planting (DAP) in the intercropping treatment increased by 25.97% compared to the monoculture treatment. The treatment with bambara groundnut as the secondary crop did not differ from the treatment with soybean as the secondary crop, but it resulted in a 19.14% higher growth rate of maize compared to the rice secondary crop. Bambara, as a legume plant, supplies nitrogen to the soil through nitrogen fixation and increases light interception. Raza et al. (2022) showed that intercropping maize with soybeans also increases the maize growth rate through similar mechanisms.

The treatment with rice as the secondary crop also did not show any difference in the growth rate of maize compared to the soybean crop. The treatment with rice as the secondary crop resulted in a maize growth rate at the age of 44-58 DAP that was 80.39% and 42.16% higher than the treatment with soybean and bambara groundnut as secondary crops, respectively, likely due to lower competition for growing space. The one-row and two-row planting patterns are more effective in increasing the maize growth rate compared to the three-row pattern. Wider planting distances reduce competition for water and nutrient absorption, consistent with Marliah (2010), who stated that closer planting distances can decrease the growth and yield of sweet maize due to more intensive competition for necessary resources. However, there was no difference in the growth rate of maize between the soybean and bambara groundnut secondary crops. The treatment with single-row and double-row patterns of secondary crops resulted in maize growth rates that were 54.43% and 42.03% higher, respectively, compared to the single-row pattern treatment.

Based on the overall comparison results of intercropping treatment with monoculture, the intercropping system yields better results compared to monoculture in terms of maize dry weight and crop growth rate during the peak vegetative phase. This indicates a better influence of legumes and rice in intercropping, which fill the growing space between the main plants, inhibit weed growth, and contribute nitrogen availability to the maize plant roots. According to Rasool et al. (2021), the synergy between maize and intercrops can inhibit weed growth by reducing the sunlight available to weeds and providing nitrogen in the soil through nitrogen fixation by legume plants. The study by Raza et al. (2022) also supports that intercropping maize with soybeans increases the growth rate of maize by enhancing light use efficiency, water use efficiency, and the benefits of soybean's nitrogen-fixing ability.

3.2 Yield Observation

Based on analysis of variance results indicate that there are no differences between the monoculture and intercropping systems in terms of the average dry weight of maize kernels. Additionally, there was no interaction between the type of companion plant and the intercropping pattern on the average kernel production of maize plants. The average production of maize plants due to the treatment of companion plant types and intercropping patterns is presented in Table 4.

Table 4. Average Production of Dry Kernel Maize Crops Due to Treatment of Intercropping Types with Intercropping Pattern.

Treatments	Dry Yield of Maize Kernel per hectare (ton.ha^{-1})
Monoculture	9,24
Intercropping	8,92
Intercrop Plant Type	
Rice	8,82±0,86
Soybean	8,60±1,57
Bambara Groundnut	9,34±0,60
LSD 5%	ns
CV (%)	10,28%
Intercropping Pattern	
One Row	8,54±1,25
Two Rows	9,54±0,90
Three Rows	8,67±0,93
LSD 5%	ns
CV (%)	9,55%

Note: Values are based on the mean ± standard deviation; ns = not significantly different based on the 5% LSD test.

Based on observations from Table 4, the variance analysis of each factor shows that maize production did not show significant differences between intercrop types and planting patterns, nor between intercropping and monoculture systems. This is due to the dominance of maize plant growth compared to intercrops and the same maize plant population in each treatment. Fitriana (2014) found that planting maize with soybeans at different plant densities did not show differences in production per unit area. Although there were no differences in maize kernel production among the treatment factors, the type of companion plant treatment with different intercropping patterns can be beneficial when viewed from the Land Equivalent Ratio (LER). The production of monoculture and intercropped maize and companion plants, as well as the LER, are presented in Table 5.

Monoculture maize plant tends to produce higher dry seed yield compared to rice and soybeans in various populations, except for the soybean and also bambara treatments in the two-row population, which yielded higher results. LER calculations show that all planting patterns yield an LER greater than 1, except for the rice and soybean one-row planting pattern. Rice and soybean in the one-row pattern tend to gives lowest yield and LER compared to other treatments.

Most treatments resulted in an LER (Land Equivalent Ratio) of more than 1, indicating that intercropping systems are more productive and efficient in land use compared to monoculture. The highest LER was achieved by two-row soybean intercropping, followed by two-row bambara, which according to Sija et al. (2022), is due to the complementary effects on the canopy structure that increase solar radiation absorption and plant biomass accumulation. A decrease in LER occurred in three-row soybean and bambara intercropping, caused by higher intercrop density and closer planting distances to maize plants, leading to competition for growing space and suboptimal sunlight distribution. Parimaladevi et al. (2019) stated that the solar radiation received by legume plants is obstructed by the taller morphology of maize plants, reducing legume photosynthesis and yield.

Table 5. Average Production and Land Equivalent Ratio (LER) of Maize Crops and Intercrops Plant Due to Monoculture and Intercropping Treatment.

Intercrop Plant and Pattern	Average Dry Seed Yield per hectare (ton.ha^{-1})				LER
	Maize	Rice	Soybean	Bambara	
Monoculture	9,24	5,2**	6**	2,31**	
Intercropping					
One Row Rice	8,59	0,29	-	-	0,99
Two Rows Rice	8,87	0,31	-	-	1,02
Three Rows Rice	8,98	0,58	-	-	1,08
One Row Soybeans	7,67	-	0,79	-	0,96
Two Rows Soybeans	10,28	-	1,63	-	1,38
Three Rows Soybeans	7,85	-	1,23	-	1,06
One Row Bambara	9,36	-	-	0,25	1,12
Two Rows Bambara	9,46	-	-	0,71	1,33
Three Rows Bambara	9,18	-	-	0,53	1,22

**) Average monoculture intercrop plant dry seed yield is obtained from monoculture planting on the same field area.

3.3 Solar Radiation Observation

Results of the variance analysis indicate that there is a significant difference between the treatment of maize plants grown in monoculture and maize plants grown in intercropping systems to interception efficiency at 86 DAP (Days After Planting). However, in intercropping treatments, there is no interaction between the type of intercrop and the intercrop pattern on the interception efficiency of maize and intercrops. The variance analysis results for each factor show that the treatment of intercrop type and the treatment of intercrop pattern do not have a significant effect on interception efficiency. The interception efficiency data due to the treatment of intercrop type and intercrop pattern are presented in Table 6.

Tabel 6. Solar Interception Efficiency and Radiation Use Efficiency Due to Treatment of Intercrop Plant and Intercrop Patterns.

Treatments	Radiation Interception Efficiency (%)	Radiation Use Efficiency (%)
Monoculture	88,02 A	4,59 A
Intercropping	94,07 B	6,19 B
Intercrop Plant Type		
Rice	92,26	6,22
Soybean	95,97	6,05
Bambara Groundnut	93,98	6,30
LSD 5%	ns	ns
CV (%)	2,41%	22,61%
Intercropping Pattern		
One Row	93,75	5,25 a
Two Rows	94,56	6,88 b
Three Rows	93,89	6,43 b
LSD 5%	ns	1,13
CV (%)	1,49%	15,64%

Note: Values followed by the same letter in the same column indicate no significant difference (uppercase letters for Orthogonal Contrast test and lowercase letters for 5% LSD test); DAP = Days After Planting; ns = not significantly different based on the 5% LSD test.

Observations in Table 6 show that intercropping treatments of maize with several types of intercrops planted in various intercrop patterns can increase interception efficiency by 6.87% higher compared to the monoculture planting system, although there are no significant differences between intercrop types or planting patterns. Maize plants in intercropping systems show more optimal growth, with dominant plant canopies in receiving sunlight. Brooker (2015) stated that the top canopy layer in intercropping systems tends to dominate solar radiation interception, while shorter plants utilize the radiation transmitted to the ground. Liu et al. (2022) added that the larger leaf area of maize plants can increase solar radiation interception.

There is also a difference between monoculture maize treatment and intercropping treatment with intercrops plant on RUE at harvest time based the results of analysis of variance. Intercropping treatment can provide interaction between the type of intercrop and the intercrop pattern on solar radiation radiation use efficiency. The variance analysis results for each factor show that the intercrop pattern significantly affects the solar radiation radiation use efficiency of maize at harvest time. Intercropping treatment can provide an RUE (Radiation Use Efficiency) result of 34.86% higher compared to monoculture treatment. The two-row and three-row intercrop patterns can provide solar radiation use efficiency results of 30.86% and 22.44% higher, respectively, compared to the one-row treatment. RUE is higher in the intercropping system, especially in the two-row planting pattern, which shows an increase in plant biomass accumulation per unit area due to the more efficient use of solar radiation in intercropping and increased diffused light. Arina (2021) found that intercropping maize with legumes increases RUE compared to monoculture because the plant canopy covers the ground well, reducing escaping solar radiation. Raza (2019) also noted that planting distance arrangements in intercropping systems can increase dry weight accumulation and radiation use efficiency.

IV. CONCLUSION

This research indicates that the intercropping system can achieve higher values of solar Interception Efficiency (IE) and Radiation Use Efficiency (RUE), with increases of 6.87% and 34.86% respectively, compared to the monoculture system. Land Equivalent Ratio (LER) reached its highest value in the treatment with intercropped soybean and two-row bambara, which was followed by an increase in solar RUE of 31.05% higher in the two-row intercropping pattern compared to the one-row treatment.

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