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Research Article

Radiation Dynamics of Sweetpotato (*Ipomoea batatas* (L.) Lam) in Response to Different Cropping Systems with a Legume Crop

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Abstract

Background and Objective: The production of sweetpotato (*Ipomoea batatas* L.) in Malaysia is far below the projected yield of approximately 20 t ha^{-1}. Two field studies were conducted to assess the mechanism underlying the interception of photosynthetically active radiation and radiation use efficiency as influenced by different cropping systems on growth performance, tuber yield and phytochemical contents of sweetpotato. **Materials and Methods:** Four treatments (sole sweetpotato, sole soybean, mixed sweetpotato-soybean and relay sweetpotato-soybean) were arranged in a four repeated Randomized Complete Block Design (RCBD). **Results:** In Study 1, sweetpotato in mixed system showed higher total dry matter, total crop yield and harvest index than relay system, but reported to be higher than sole system in Study 2. The land equivalent ratio greater than 1 was shown by mixed system in Study 1 and mixed and relay systems in Study 2, which means over yielding occurred and the intercrops were more productive than the sole system. In Study 1, critical leaf area index as achieved by sweetpotato in sole system (4.17 at 96 Days After Sowing (DAS)), mixed system (4.44 at 90 DAS) and relay system (4.85 at 108 DAS), meanwhile, in Study 2, only sweetpotato on sole system (3.92 at 72 DAS) and mixed system (4.14 at 71 DAS) were achieved when radiation interception reached 95%. In addition, the highest levels of lightness, antioxidant activity, total flavonoid and total phenolic contents were found in the mixed system. **Conclusion:** Mixed intercropping of sweetpotato and soybean could produce high yield through more efficient resource use.

Key words: *Ipomoea batatas* L., cropping systems, land equivalent ratio, photosynthetically active radiation, radiation use efficiency

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Competing Interest: The authors have declared that no competing interest exists.

Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

Sweetpotato (*Ipomoea batatas* (L.) Lam) is one of the important tuber crops belongs to the morning glory family, Convolvulaceae. It is a perennial dicotyledon and a starchy staple food source[1]. According to Hue *et al.*[2], sweetpotato originated from northwest of South America and it is planted mainly for its tuber. It ranks seventh after other food crops; wheat, rice, corn, potato, barley and cassava[3]. Among tuber crops, sweetpotato is the second after Irish potato[4].

Sweetpotato is considered as a nutritionally rich food in terms of macro and micro-nutrients which exist in its tubers[5,6]. Sweetpotato tubers are good for maintaining and improving health and it has been found to be rich in nutritional values (carbohydrate, protein and dietary fiber), vitamins A, B, B6, C, E and minerals (iron and potassium) in favorable amounts[5,7]. According to Wang *et al.*[8], sweetpotato has unique composition in which it gives various health benefits, such as; anti-aging, anti-cancer, anti-diabetic, anti-inflammatory, anti-oxidative, anti-microbial, anti-obesity and hepatoprotective.

Sweetpotato is usually planted as a single crop. The sweetpotato production is expected to increase if sweetpotato is combined with other compatible crops such as legumes. According to Matusso *et al.*[9], legume intercropping is recognized among the small scale farmers in developing countries as a common cropping system. In some countries, like Nigeria and the Southern Guinea Savanna, Brazil, Caribbean islands, Indonesia, Papua New Guinea, Paraguay and Peru[10,11] sweetpotato has been intercropped with legumes.

Intercropping sweetpotato with legume gives many advantages including reducing nutrient leaching and soil erosion and suppressing weeds[12,13]. Wang *et al.*[14] also stated that the presence of legume crops could fix nitrogen from atmosphere and supply nitrogen to other plants in the intercropped plot. Legume intercrops also can reduce the infestation of diseases and pests and lower the risk of crop failure. In addition, according to Duchene *et al.*[15], legume intercrops proved to be capable in increasing higher yield and land use efficiency value higher than 1.

Besides the cropping system itself, the rate of photosynthesis that subsequently affects yield is determined by the incidence of quantum flux intercepted by a crop canopy. Reziq *et al.*[16] reported that the higher the intercrop productivity, the higher the Photosynthetically Active Radiation (PAR) interception. Brooker *et al.*[17] reported that legumes used the captured solar radiation more effectively than sole crops in legume intercrops. This is consistent with Kiseve[18], who reported that legumes were shorter and had a shadier canopy to use the light transmitted to the ground.

The current study was conducted to assess the interception mechanism for PAR and Radiation Use Efficiency (RUE) in influencing yield potential, growth performance and phytochemical contents of sweetpotato planted in different cropping systems with a legume crop (soybean).

MATERIALS AND METHODS

Experimental site and designs: Two field studies were performed at Field 15, Faculty of Agriculture, Universiti Putra Malaysia, Serdang, Malaysia (2°59'N, 101°44'E, 61 m a.s.l.). All studies were conducted in 2016 (Study 1) and 2017 (Study 2) for a period of 6 months each. Two different crops were used throughout the period of the studies, (1) Sweetpotato (SP) (*Ipomoea batatas* L. var. Bukit Naga) and (2) Soybean (SB) (*Glycine max* L. var. Palmetto). Irrigation was carried out twice a day using a sprinkler system. Agronomic practices for each crop were performed as recommended.

Research procedure: The studies consisted of four treatments namely: (1) Sole sweetpotato (Sole SP), (2) Sole soybean (Sole SB), (3) Mixed sweetpotato-soybean (Mixed SPSB) and (4) Relay sweetpotato-soybean (Relay SPSB). In Study 1, SP was first grown in relay system followed by SB, meanwhile, in Study 2, SB was first grown followed by SP (due to the rapid growth of SP planted in Study 1 causing stunted early growth of SB).

Both studies consisted of 28 plots of treatments, each measured 6.0×2.75 m and the distance between plots was 1.0 m. Each treatment consisted of four rows, each row measuring 6.0×0.5 m and the inter-row was 0.25 m. In sole treatments, there were four rows of the same plants. For mixed and relay treatments, each treatment consisted of 2 rows of main crop (SP) and 2 rows of intercrops (SB). Every row consisted of 22 plants. The crops were arranged in 1:1 arrangement and the planting distance between plants was 0.25 m. Both studies were carried out with four replications in Randomized Complete Block Design (RCBD).

Data collection and statistical analysis: Physiological measurements of plants included Total Dry Matter (TDM), Total Crop Yield (TCY), Harvest Index (HI), Land Equivalent Ratio (LER), maximum Leaf Area Index (LAI_{max}), radiation intercepted, total intercepted PAR and RUE. Destructive sampling was performed for each treatment every two weeks of the growing season. Li-COR leaf area meter was used to measure leaf area. The HI was determined as the ratio of crop yield to total above-ground crop biomass. The LER was calculated as the sum of the fractions of the intercropped yields divided by the sole crop yield. The LAI_{max} was determined as the highest LAI from the entire growing season.

AccuPAR Ceptometer was used to determine the fraction of PAR intercepted by the canopy using incident PAR above and below the canopy of leaves. The relationship between fractions of radiation intercepted with LAI for the different cropping system was determined. The critical LAI (LAI_{crit}) at which PAR had been intercepted at 95% was determined by using the exponential curve shown in each treatment. The linear slope of the relationship between total dry matter and intercepted PAR accumulated was used to calculate RUE.

Quality evaluation including Total Flavonoid Content using aluminium chloride assay[19], Total Phenolic Content using the Folin-Ciocalteu method[20], Total β-carotene content using non-saponification method[21], 1,1-diphenyl-2-picrylhydrazyl (DPPH) free radical scavenging activity[22] and chromaticity values (lightness (L*), chroma (C*) and hue (h*)) were carried out on the SP tubers. The representative samples of each plot were taken.

Data analysis: Data obtained were analyzed by using One-way Analysis of Variance (ANOVA) of Statistical Analysis System (SAS), Version 9.4. Treatment means comparison were made by using the Least Significant Difference (LSD) test at $p \leq 0.05$ for significance.

RESULTS

There were significant differences in Total Dry Matter (TDM) among all treatments in both Study 1 and Study 2 ($p<0.05$) (Table 1). The highest TDM was shown by sweetpotato (SP) in Mixed SPSB (13560 kg ha^{-1}, 10118 kg ha^{-1}) compared to Sole SP (10991 kg ha^{-1}, 9163 kg ha^{-1}) about 18.95 and 9.44%, respectively. Meanwhile, soybean (SB) in Mixed SPSB (4207 kg ha^{-1}, 6587 kg ha^{-1}) gave higher TDM compared to Relay SPSB (1196 kg ha^{-1}, 3441 kg ha^{-1}) about 71.57 and 47.76%, respectively, in Study 1 and 2.

From Table 1, Total Crop Yield (TCY) of component crops, SP and SB also were higher in mixed system (4770 kg ha^{-1}, 2226 kg ha^{-1}) compared to relay system (2639 kg ha^{-1}, 322 kg ha^{-1}) in Study 1. However, in Study 2, there was no significant difference reported for SP and SB in mixed and relay systems ($p<0.05$). The SP in Mixed SPSB (2493 kg ha^{-1}) showed higher TCY than Sole SP (1951 kg ha^{-1}) about 21.74%.

Besides, Table 1 indicated the Harvest Index (HI) in Study 1 was found to be higher in Mixed SPSB (34.94%; 58.26%) than Relay SPSB (27.29%, 27.23%) in both component crops (SP and SB). In Study 2, HI for SB in Relay SPSB (47.46%) was higher than Mixed SPSB (24.51%), meanwhile, HI of SP was not significantly different in Mixed SPSB (24.63%) and Relay SPSB (24.03%) ($p<0.05$).

As shown in Table 2, there was no significant difference in maximum Leaf Area Index (LAI_{max}) and Radiation Use Efficiency (RUE) among all the evaluated treatments for SP in Study 1 and SB in Study 2 ($p>0.05$). In Study 1, SB in Mixed SPSB (1.94) and Relay SPSB (1.21) showed lower LAI_{crit} value than Sole SB (3.13). Besides, SP in Mixed SPSB (5.66) was reported to be higher than Relay SPSB (3.55) in Study 2. In addition, RUE

Table 1: Total Dry Matter (TDM), Total Crop Yield (TCY) and Harvest Index (HI) of sweetpotato (SP) and soybean (SB) in different cropping systems in Study 1 and 2

	Total Dry Matter (kg ha^{-1})				Total Crop Yield (kg ha^{-1})				Harvest Index (%)			
	1		2		1		2		1		2	
Cropping system	SP	SB	SP	SB	SP	SB	SP	SB	SP	SB	SP	SB
Sole SP	10991^{b}		9163^{b}		4299^{a}		1951^{b}		38.82^{a}		21.30^{b}	
Sole SB		5648^{a}		3531^{b}		1708^{a}		1258^{a}		31.35^{ab}		35.61^{ab}
Mixed SPSB	13560^{a}	4207^{a}	10118^{a}	6587^{a}	4770^{a}	2226^{a}	2493^{a}	1608^{a}	34.94^{a}	58.26^{a}	24.63^{a}	24.51^{b}
Relay SPSB	9655^{b}	1196^{b}	10412^{a}	3441^{b}	2639^{b}	322^{b}	2501^{a}	1561^{a}	27.29^{b}	27.23^{b}	24.03^{a}	47.46^{a}
Significance	**	**	*	**	*	**	**	ns	*	ns	*	*

Means within column followed by the same letter are not significantly different by LSD, ($p \leq 0.05$), *Significant at $p \leq 0.05$, **Significant at $p \leq 0.01$, ***Significant at $p \leq 0.0001$, ns: Not significant

Table 2: Maximum Leaf Area Index (LAI_{max}) and Radiation Use Efficiency (RUE) of sweetpotato (SP) and soybean (SB) in different cropping systems in Study 1 and 2

	Maximum Leaf Area Index				Radiation Use Efficiency (g MJ^{-1})			
	1		2		1		2	
Cropping system	SP	SB	SP	SB	SP	SB	SP	SB
Sole SP	4.65^{a}		4.79^{ab}		1.78^{a}		1.43^{b}	
Sole SB		3.13^{a}		1.83^{a}		0.86^{b}		1.66^{a}
Mixed SPSB	4.60^{a}	1.94^{b}	5.66^{a}	1.58^{a}	2.22^{a}	1.40^{a}	1.63^{a}	2.06^{a}
Relay SPSB	4.95^{a}	1.21^{b}	3.55^{b}	1.88^{a}	1.85^{a}	0.27^{c}	1.46^{b}	1.75^{a}
Significance	ns	**	*	ns	ns	**	*	ns

Means within column followed by the same letter are not significantly different by LSD ($p \leq 0.05$), *Significant at $p \leq 0.05$, **Significant at $p \leq 0.01$, ***Significant at $p \leq 0.0001$, ns: Not significant

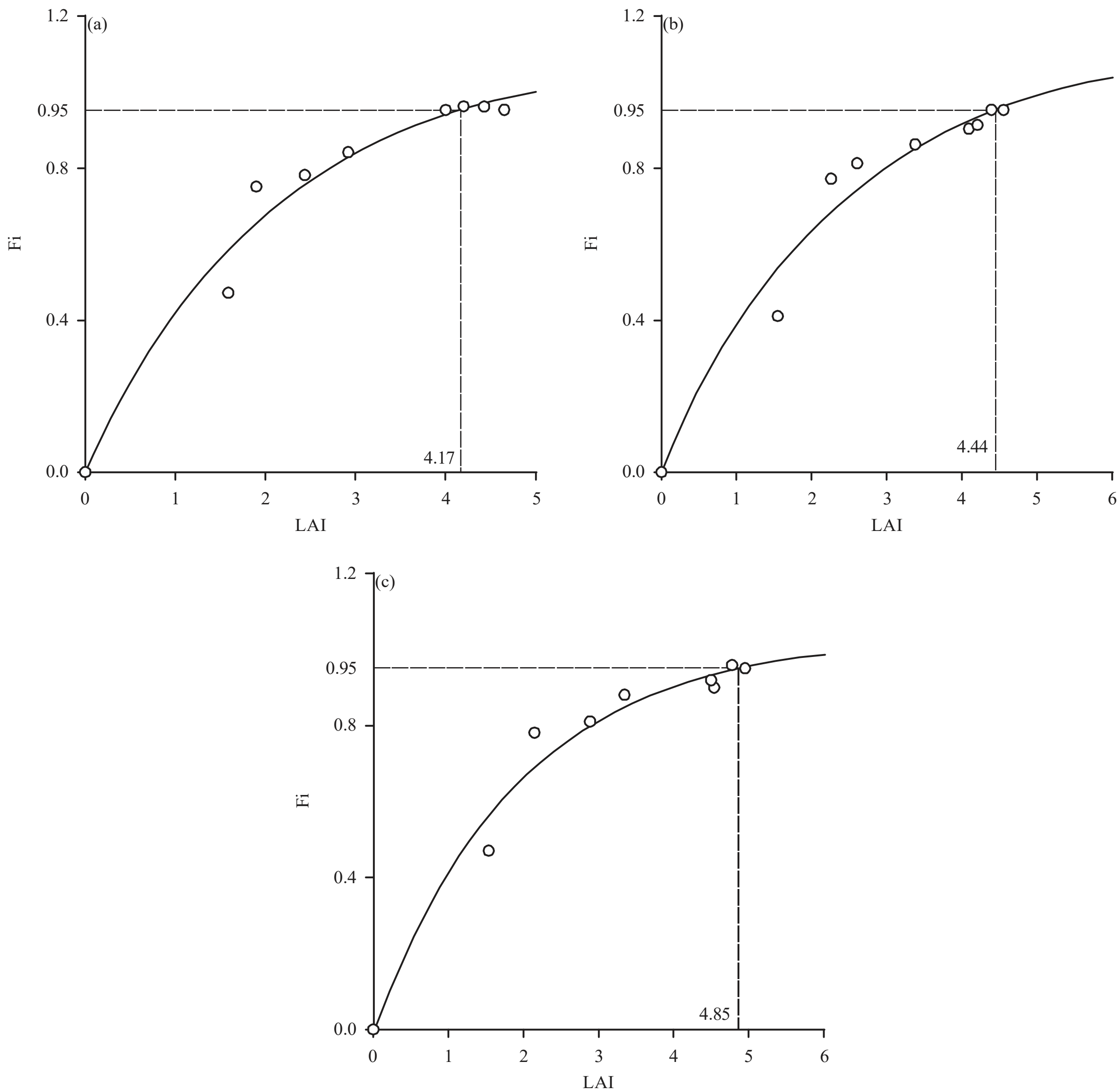

Fig. 1(a-c): Relationship between the fraction of radiation intercepted (Fi) and Leaf Area Index (LAI) of sweetpotato (SP) in (a) Sole SP (Sole sweetpotato), (b) Mixed SPSB (Mixed sweetpotato-soybean) and (c) Relay SPSB (Relay sweetpotato-soybean) in Study 1

The solid line fitted exponential curve, (a) $y = 1.10\ (1-e^{-0.45x})$ ($R^2 = 0.9706$), (b) $y = 1.13(1-e^{-0.41x})$ ($R^2 = 0.9645$) and (c) $y = 1.03(1-e^{-0.52x})$ ($R^2 = 0.9757$), The dashed line reflects the intercepted 95% Photosynthetically Active Radiation (PAR) and the index of the critical area of the leaf (LAI_{crit})

value in SB in Study 1 showed the highest under Mixed SPSB (1.40 g MJ^{-1}), while Sole SB (0.86 g MJ^{-1}) had higher RUE than in Relay SPSB (0.27 g MJ^{-1}) ($p>0.05$). As reported in Study 2, RUE value of SP in Mixed SPSB (1.63 g MJ^{-1}) was higher compared to Sole SP (1.43 g MJ^{-1}) and Relay SPSB (1.46 g MJ^{-1}) ($p>0.05$).

Mixed SPSB showed larger Land Equivalent Ratio (LER) value than 1 in Study 1 (2.22) and Study 2 (2.56), indicating the yield advantage for intercrops (Table 3). However, in Study 1, the Mixed SPSB showed higher LER (2.56) than Relay SPSB (0.85), but Relay SPSB was judged to be statistically non-significant to sole cropping (1.00) ($p<0.05$).

Study 1 indicated that SP in all evaluated treatments had achieved critical LAI (LAI_{crit}) when intercepting 95% of intercepted PAR as presented in Fig. 1. The SP in all evaluated treatments achieved LAI_{crit} at 95% PAR interception (Fig. 1a-c). Meanwhile, SB in all treatments did not intercept the radiation up to 95% (Fig. 2a-c). Sole SP achieved LAI_{crit} (4.17) at 96 Days After Sowing (DAS), Mixed SPSB achieved LAI_{crit} (4.44) at 90 DAS and Relay SPSB achieved LAI_{crit} (4.85) at

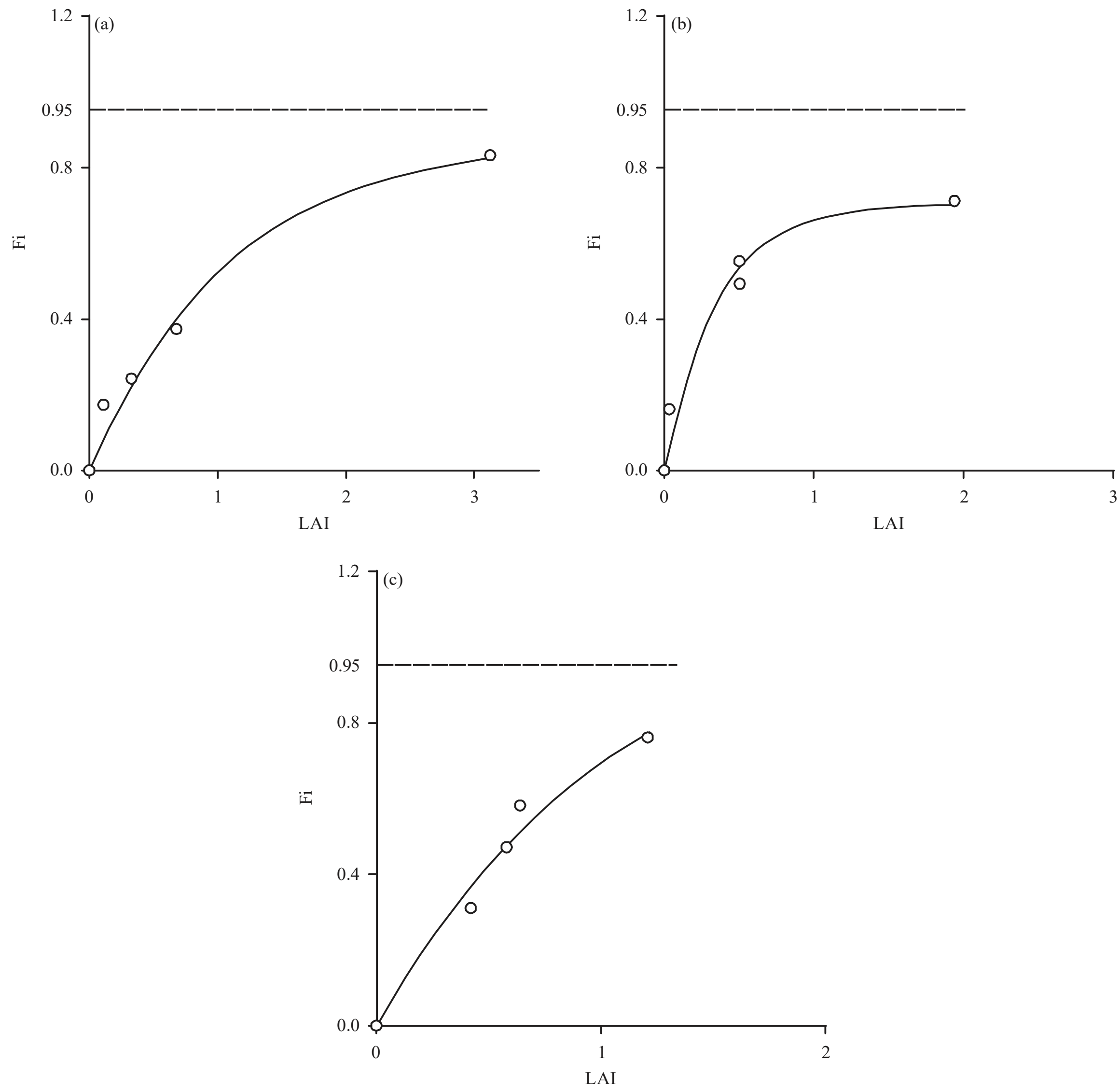

Fig. 2(a-c): Relationship between the fraction of radiation intercepted (Fi) and Leaf Area Index (LAI) of soybean (SB) in (a) Sole SB (Sole sweetpotato), (b) Mixed SPSB (Mixed sweetpotato-soybean) and (c) Relay SPSB (Relay sweetpotato-soybean) in Study 1

The solid line fitted exponential curve, (a) $y = 0.88\ (1-e^{-0.91x})$ ($R^2 = 0.9775$), (b) $y = 0.70\ (1-e^{-2.83x})$ ($R^2 = 0.9628$) and (c) $y = 1.15\ (1-e^{-0.92x})$ ($R^2 = 0.9751$), The dashed line reflects the intercepted 95% Photosynthetically Active Radiation (PAR) and the index of the critical area of the leaf (LAI_{crit})

108 DAS (Fig. 3a-c). However, in Study 2, only SP in Sole SP and Mixed SPSB achieved LAI_{crit} at 95% of intercepted PAR (Fig. 4a-b). Since the other treatments did not intercept the radiation up to 95%, therefore, LAI_{crit} and DAS could not be identified (Fig. 4c, Fig. 5a-c). Sole SP achieved LAI_{crit} (3.92) at 72 DAS and Mixed SPSB achieved LAI_{crit} (4.14) at 71 DAS (Fig. 6a-b).

Table 3 indicates the highest total intercepted PAR in Study 1 was shown by Sole SP (545.56 MJ m^{-2}) followed by Mixed SPSB (502.58 MJ m^{-2}) and Relay SPSB (476.02 MJ m^{-2}), but there was no significant difference between these treatments. In Study 2, Relay SPSB showed the highest intercepted PAR (620.18 MJ m^{-2}) followed by Sole SP (492.40 MJ m^{-2}) and Mixed SPSB (469.19 MJ m^{-2}). The lowest total intercepted PAR was shown by Sole SB in both cropping seasons, 2016 (303.13 MJ m^{-2}) and 2017 (230.79 MJ m^{-2}), respectively.

Phytochemical contents of SP tubers are presented in Table 4. In Study 1, the chromaticity values (Lightness (L*), Chroma (C*) and Hue (H*)), the Total Flavonoid Content (TFC), Total Phenolic Content (TPC) and of 1, 1-diphenyl-2-

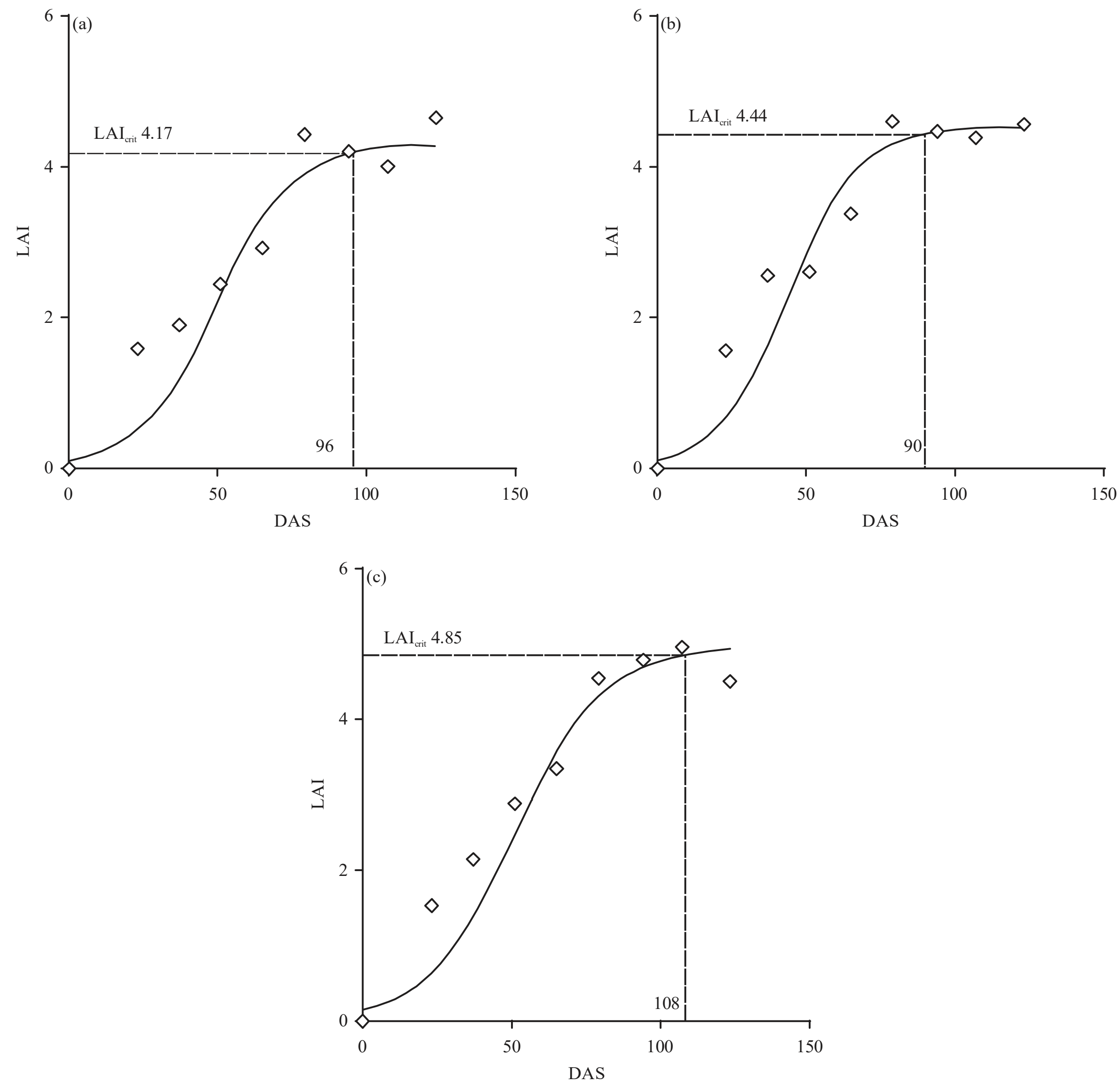

Fig. 3(a-c): Relationship between the Leaf Area Index (LAI) and Days After Sowing (DAS) of sweetpotato (SP) in (a) Sole SP (Sole sweetpotato), (b) Mixed SPSB (Mixed sweetpotato-soybean) and (c) Relay SPSB (Relay sweetpotato-soybean) in Study 1

Table 3: Land Equivalent Ratio (LER) and Photosynthetically Active Radiation (PAR) in different cropping systems in Study 1 and 2

	Land Equivalent Ratio		Photosynthetically Active Radiation (MJ m^{-2})	
Cropping system	1	2	1	2
Sole SP	1.00^{b}	1.00^{b}	545.56^{a}	492.40^{b}
Sole SB	1.00^{b}	1.00^{b}	303.13^{c}	230.79^{c}
Mixed SPSB	2.22^{a}	2.56^{a}	502.58^{b}	469.19^{b}
Relay SPSB	0.85^{b}	2.55^{a}	476.02^{b}	620.18^{a}
Significance	***	***	***	***

Means within column followed by the same letter are not significantly different by LSD ($p \leq 0.05$), *Significant at $p \leq 0.05$, **Significant at $p \leq 0.01$, ***Significant at $p \leq 0.0001$, ns: not significant

picrylhydrazyl (DPPH) free radical scavenging activity and Total β-carotene content of SP tubers in different cropping systems were reported with no significant difference among them (p>0.05).

In Study 2, the value lightness (L*) was higher in Sole SP (75.97) compared to Mixed SPSB (72.61), but no significant difference between Mixed SPSB and Relay SPSB (74.84) were detected. A highly significant difference was reported in TFC, TPC and DPPH of SP tuber in all evaluated treatments except for Total β-carotene content, with no significant difference among them (p>0.05).

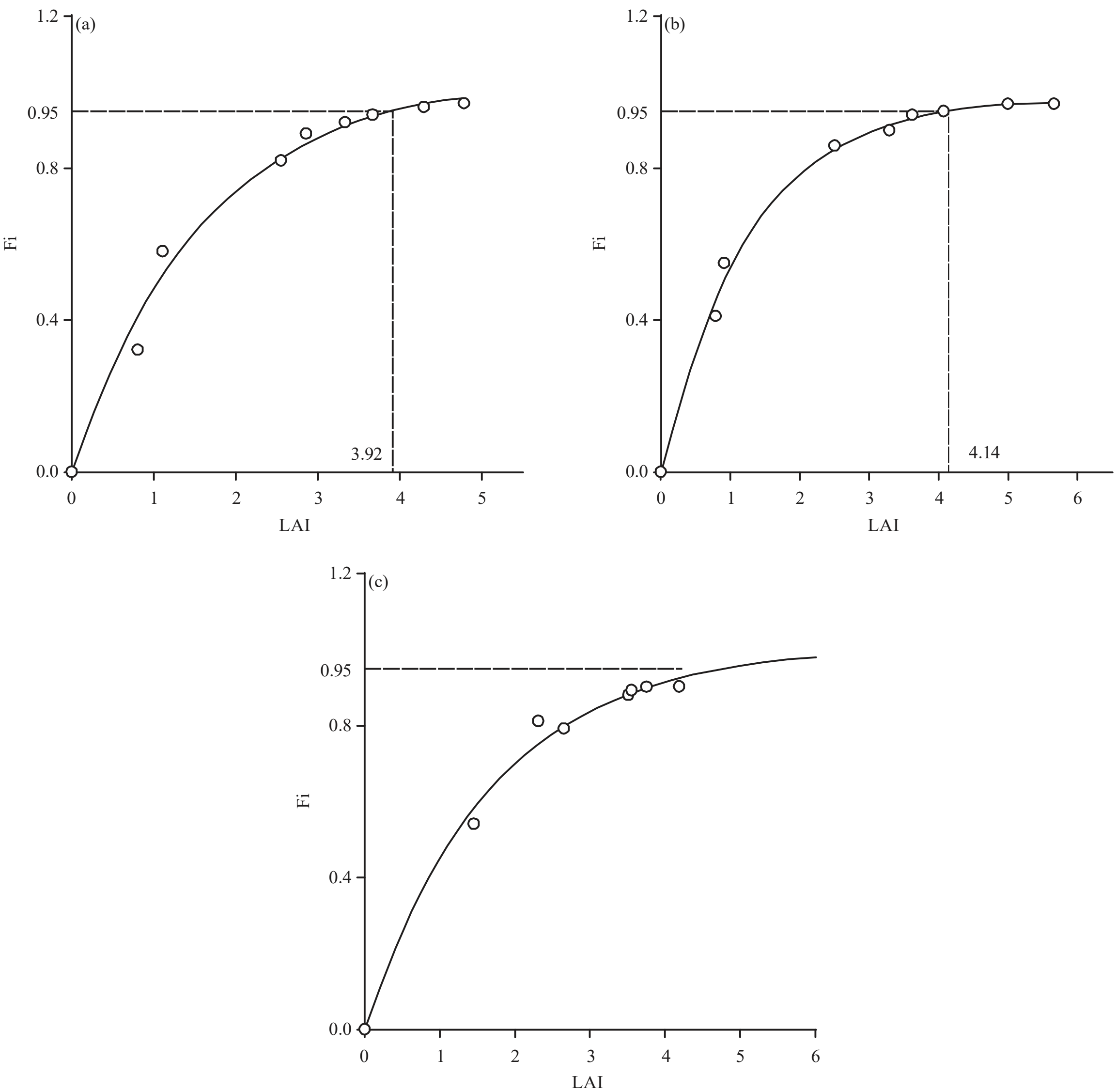

Fig. 4(a-c): Relationship between the fraction of radiation intercepted (Fi) against Leaf Area Index (LAI) of sweetpotato (SP) in (a) Sole SP (Sole sweetpotato), (b) Mixed SPSB (Mixed sweetpotato-soybean), (c) Relay SPSB (Relay sweetpotato-soybean) in Study 2

The solid line fitted exponential curve, (a) $y = 1.04\,(1-e^{-0.62x})$ ($R^2 = 0.9866$), (b) $y = 0.99\,(1-e^{-0.80x})$ ($R^2 = 0.9950$), (c) $y = 1.01\,(1-e^{-0.59x})$ ($R^2 = 0.9915$), The dashed line reflects the intercepted 95% Photosynthetically Active Radiation (PAR) and the index of the critical area of the leaf (LAI_{crit})

The TFC and TPC were the highest in Mixed SPSB with 1.51 mg Quercetin g^{-1} FW and 0.33 mg GA g^{-1} FW, respectively. Due to high values of these phytochemical contents, the results showed that Mixed SPSB possessed the highest antioxidant activity (57.21%) among all tested cropping systems as evaluated using DPPH reagent.

In addition as seen in Table 4, the results indicated that Mixed SPSB was higher in TFC (1.51 mg Quercetin g^{-1} FW), TPC (0.33 mg GA g^{-1} FW), antioxidant activity (57.21%) than those detected in Relay SPSB (0.84 Quercetin g^{-1} FW, 0.28 mg GA g^{-1} FW, 50.59%), whereas, Sole SP (0.77 mg Quercetin g^{-1} FW, 0.21 mg GA g^{-1} FW, 39.08%) was evaluated to be lower than both mixed intercropping systems. Besides, TFC was similar in Sole SP (0.77 mg Quercetin g^{-1} FW) and Relay SPSB (0.84 mg Quercetin g^{-1} FW). However, a significant difference was reported in TPC and antioxidant activity

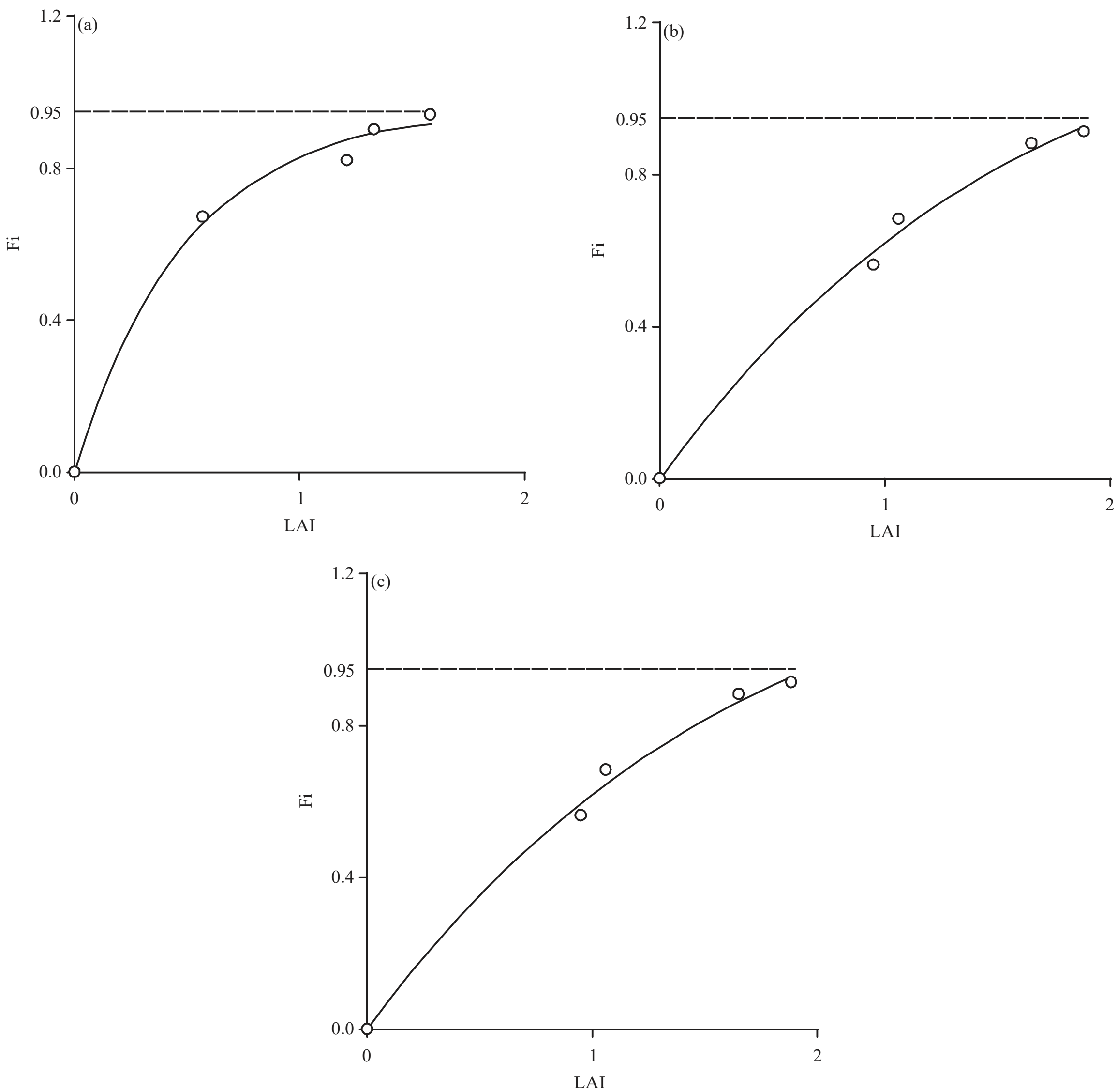

Fig. 5(a-c): Relationship between the fraction of radiation intercepted (Fi) against Leaf Area Index (LAI) of soybean (SB) in (a) Sole SB (Sole soybean), (b) Mixed SPSB (Mixed sweetpotato-soybean) and (c) Relay SPSB (Relay sweetpotato-soybean) in Study 2

The solid line fitted exponential curve, (a) $y = 1.10\ (1-e^{-0.91x})$ ($R^2 = 0.9974$), (b) $y = 0.95\ (1-e^{-2.06x})$ ($R^2 = 0.9938$) and (c) $y = 1.35\ (1-e^{-0.61x})$ ($R^2 = 0.9942$), The dashed line reflects the intercepted 95% Photosynthetically Active Radiation (PAR) and the index of the critical area of the leaf (LAI_{crit})

Table 4: Quality evaluation of sweetpotato (SP) tuber in different cropping systems in Study 1 and 2

	Chromaticity values						Phytochemical contents							
	Lightness (L*)		Chroma (C*)		Hue (h°)		TPC (mg GA g^{-1} FW)		TFC (Quercetin g^{-1} FW)		DPPH free radical scavenging activity (%)		Total*	
Cropping system	1	2	1	2	1	2	1	2	1	2	1	2	1	2
Sole SP	76.27^{a}	75.97^{a}	41.14^{a}	40.84^{a}	60.97^{a}	61.94^{a}	0.14^{a}	0.21^{c}	0.14^{a}	0.77^{b}	42.65^{a}	39.08^{c}	1.96^{a}	0.97^{a}
Mixed SPSB	76.09^{a}	72.61^{b}	41.53^{a}	38.29^{a}	61.67^{a}	59.96^{a}	0.13^{a}	0.33^{a}	0.14^{a}	1.51^{a}	46.48^{a}	57.21^{a}	2.11^{a}	1.71^{a}
Relay SPSB	75.82^{a}	74.84^{ab}	41.31^{a}	40.63^{a}	61.75^{a}	61.02^{a}	0.12^{a}	0.28^{b}	0.14^{a}	0.84^{b}	45.19^{a}	50.59^{b}	1.77^{a}	1.27^{a}
Significance	ns	*	ns	ns	ns	ns	ns	***	ns	***	ns	***	ns	ns

Means within column followed by the same letter are not significantly different by LSD ($p \leq 0.05$), *Significant at $p \leq 0.05$, **Significant at $p \leq 0.01$, ***Significant at $p \leq 0.0001$, ns: Not significant, Solo SP: Sole sweetpotato, Solo SB: Sole soybean, Mixed SPSB: Mixed sweetpotato-soybean and Relay SPSB: Relay sweetpotato-soybean, TPC: Total phenolic content, TFC: Total flavonoid content, DPPH: 1,1-diphenyl-2-picrylhydrazyl, *: Total β-carotene content (µg β-carotene g^{-1} FW)

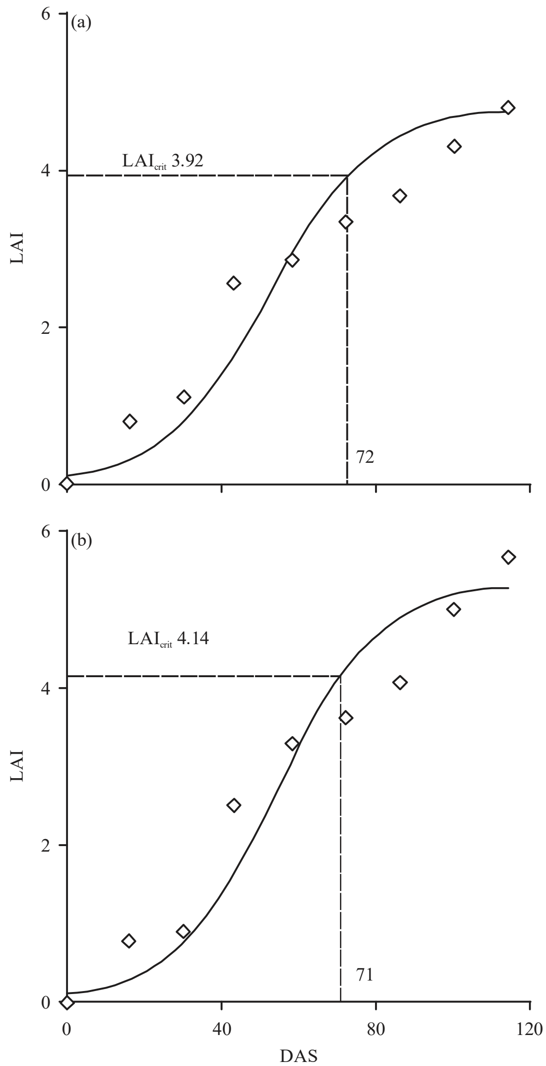

Fig. 6(a-b): Relationship between the Leaf Area Index (LAI) of sweetpotato (SP) against Days After Sowing (DAS) in (a) Sole SP (Sole sweetpotato), (b) Mixed SPSB (Mixed sweetpotato-soybean) in Study 2

among Sole SP and Relay SPSB. The results for TPC and antioxidant activity showed that Relay SPSB (0.28 mg GA g^{-1} FW, 50.59%) was higher than Sole SP (0.21 mg GA g^{-1} FW, 39.08%).

DISCUSSION

The Total Dry Matter (TDM) achieved by sweetpotato (SP) in mixed system was higher than sole system in both cropping seasons (Table 1). This was because complimentary effects occurred between the component crops when they separated their peak demands for light, moisture and nutrients, therefore, they could utilize the environmental resources efficiently[23]. According to Undie *et al.*[24], less intra-specific competition than inter-specific competition occurred in using limited resources between crops. Besides, in Study 1, TDM of SP in relay system was similar to sole system and TDM of soybean (SB) was higher in sole system compared to relay system. Meanwhile, the results in Study 2 for TDM of SP and SB were vice versa to Study 1. This was because in Study 1, the vigorous growth of SP in the relay system caused the Relay SB to be stunted in the middle growing stage and the allelopathic effect by SP probably inhibited the growth and development of neighboring plant (Relay SB)[25,26].

Theoretically, Harvest Index (HI) increases with the increment in grain yield[27]. This can be proven from both cropping seasons in the present study which showed SP in sole and mixed systems had resulted higher HI than relay systems, thereby, resulting in higher HI value (Table 1). Besides, Total Crop Yield (TCY) and HI of SB in mixed system were higher than relay system in Study 1. However, the result was in contrast with Study 2, which showed the TCY of SB in mixed and relay to be similar, but the HI value of Relay SB was higher compared to mixed SB. The reasons might have been due to homogeneity and heterogeneity of the soil and uptake of nutrients by the crops. The nutrient uptake would have improved dry matter, but at the same time reduced HI, possibly by increasing leaf area leading to mutual shading[28].

Both mixed systems in Study 1 and Study 2 showed the Land Equivalent Ratio (LER) value larger than 1 in which all the intercrops (SP and SB) in the system utilized the limiting resources such as; light, nutrients and water more efficiently than sole system[29,30]. In a previous study, Anderson[31] stated that the intercrops of pea and barley showed complementarity in nitrogen use since legumes were capable of fixing atmospheric nitrogen and supplying nitrogen to other plants in the system. However, in Study 1, the relay system was judged to be statistically non-significant to sole system. This was because late-planted crops often grew under the canopy shade of early-planted tall crops, resulting in a decrease in late-planted biomass during the shade period[32]. Besides, the late-planted crop experienced a reduced level of nitrogen in the soil, which led to yield reduction[33].

The SP is able to produce all the energy needed to sustain maximum tuber growth when critical Leaf Area Index (LAI_{crit}) reached 3-4 when intercepting 95% of Photosynthetically Active Radiation (PAR) interception[34]. This statement can be proved in the present study, in which SP in all evaluated treatments in Study 1 (Fig. 1) and in sole and mixed systems in

Study 2 (Fig. 4) had achieved LAI_{crit} when intercepting 95% of intercepted PAR. The SP had higher leaf area and bigger leaf size to dominate and capture more light[2,35]. In addition, SB did not reach LAI_{crit} in all evaluated treatments in both cropping seasons. This finding was in contrast with Schwerz *et al*.[36], where SB intercepted 95% PAR interception when reaching LAI_{crit} of 3.9. However, SB in all treatments only achieved maximum Leaf Area Index (LAI_{max}) below 3.2 (Table 2). This was because SB had smaller leaf size and lower leaf area, which resulted in insufficient amount of light been captured[37,38].

As presented in Table 3, Sole SB resulted in the lowest total intercepted PAR in both cropping systems. This was due to the self-shading of plants which reduced the net amount of leaf area subjected to direct sunlight, thereby lower the total PAR interception[39]. In Study 1, the total intercepted PAR of mixed system was lower than Sole SP. Growing plant canopy of one crop would lower PAR above other crops canopy in an intercropping system, thereby, reducing the fraction of radiation intercepted (Fi)[40]. According to Liu *et al*.[41], the Fi value was affected by the canopy structure and crop geometry. Meanwhile, in Study 2, relay system was reported to be higher than mixed system in total intercepted PAR (Table 3). The finding is in line with the previous study by Wallace *et al*.[42] on relay intercropping soybean-wheat, showing the effects of increased shade on soybean plants by the wheat canopy and the longer period between soybean planting and wheat harvest would have a greater impact on the growth performance of soybean.

Radiation Use Efficiency (RUE) of intercropping systems was higher than those of sole cropping[43]. This was proven in present study, where the RUE value of SB in Study 1 was higher in mixed system compared to sole system (Table 2). Possible explanation for this finding includes the differences between sole and mixed crops in light distribution in the plant canopy in intercropping and sole cropping systems[44]. This was supported by PAR value shown by mixed system which was lower than sole system, proved that the shorter and more shaded legume grown in the mixed system used captured solar radiation more efficiently compared to sole system, therefore, resulting in lower RUE over sole cropping soybean. The RUE is related to the LAI, in which higher LAI is crucial for the production of biomass and this accumulated production of biomass is positively and linearly linked with the strength radiation interception[45]. Besides, the RUE value of SB in relay system was lower than mixed system. This probably was due to allelopathic effect from SP which could have inhibited the growth and development of SB which caused the SB in relay system were stunted in the early growing stage, therefore, resulted in less growth of SB leaves and stems. The finding is in line with Du *et al*.[23] and Wang *et al*.[46] in which they found that the lesser growth of SB plants in relay intercropping with SP had resulted in low LAI, PAR value as well as RUE and crop yield.

The results of Study 2 were vice versa with Study 1, which indicated that the SP in mixed system showed higher RUE than Sole SP, meanwhile, the intercrop (SB) gave similar RUE value to Sole SB (Table 2). The findings in this present study are similar to the previous studies in intercropping millet with groundnut by Marshall and Willey[47], in intercropping corn with bean by Tsubo and Walker[48] and in intercropping corn with peanut by Awal *et al*.[49]. In their studies, the dominant plants (millet or corn) in intercropping system had similar RUE value to sole cropping, but the subordinate plants (groundnut, bean or peanut) had greater RUE of short statured crops in intercropping than sole cropping[50]. The claim is supported by Liu *et al*.[38], who stated that RUE value was higher in intercropping than sole cropping due to less light saturation and diffused light effect in an intercropping system. Meanwhile, the similar RUE of SB in all cropping systems was due to taller crops are able to intercept light at the upper layer, meanwhile, whereas the shorter plants (SP) only use the transmitted light to the ground.

Table 4 shown the quality evaluation of SP tubers under implementation of different cropping systems. Study 2 indicated that the quality evaluation including the value lightness (L*), antioxidant activity, Total Flavonoid Content (TFC) and Total Phenolic Contents (TPC) were shown to be the highest under mixed intercropping (Table 4). This was probably due to the effects of canopy architecture and the light exposure which could affect the accumulation of phytochemicals[51]. Sampaio *et al*.[52] also reported that high level of solar radiation had caused the reduction in photosynthetic rate and consequently increased the plant phytochemicals. From the present study, the smaller leaf size and lower leaf area of SB had resulted in increased light exposure on SP plants in the system, which encouraged the phenolic compounds synthesis and therefore, antioxidant activity in the plant[38,51].

The TCY in the present study was lower than targeted production yield (average commercial yield production) which did not achieve the expected yield of the crop of about 20 t ha^{-1}. There could have been several factors such as the soil condition (soil type, soil compactness and soil nutrients) and suitable crop combinations (combination with legume or cereal crops) that might have affected the growth and tuber production of sweetpotato.

Therefore, the evaluation of different soil condition and suitable crop combinations is recommended to increase tuber size and improve yield production.

CONCLUSION

As overall, mixed intercropping is recommended to be practiced by farmers compared to sole cropping as it can produce high yields of main crops and intercrops by using resources more efficiently. Besides, mixed intercropping can also shorten the planting period over relay intercropping, thereby can better utilize farm resources and inputs.

SIGNIFICANCE STATEMENT

This study discovered the association of Photosynthetically Active Radiation and Radiation Use Efficiency and optimum combination of tuber and legume crops cultivated in response to different cropping systems that can be beneficial for farmers to enhance the yield of sweetpotato, get better income, maximize land used efficiency, enrich soil nutrient and in a bigger scope gearing towards sustainable agroecosystem by increasing biodiversity (intercropping). This study will help the researchers to uncover the critical areas of efficiency in utilization of light interception and radiation use in different intercropping systems (mixed and relay systems) over sole cropping that many researchers were not able to explore. Thus, a new theory on light dynamics as affected by cropping systems and any possibility of crop combinations, may be arrived at.

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