Land Efficiency and Phosphate Fertilization in Sugarcane-Soybean Intercropping Using Local AMF under Saturated Soil Culture in Tidal Swamps

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Abstract. Tidal swamp land in Indonesia holds great potential for agricultural development but remains underutilized due to soil acidity and low nutrient availability. Integrating arbuscular mycorrhizal fungi (AMF) and efficient intercropping systems may improve land productivity and nutrient use efficiency in such challenging environments. This study evaluated the effects of local AMF inoculation and phosphate fertilization rates on the growth, productivity, and land-use efficiency of sugarcane–soybean intercropping under a saturated soil culture system in tidal swamps. The experiment used a randomized complete block design with two factors: AMF inoculation (with and without AMF) and four P fertilizer doses (0, 36, 72, and 108 kg ha^{-1} P_2O_5). AMF inoculation significantly increased sugarcane and soybean productivity in both monoculture and intercropping systems. Sugarcane yield increased by 86.7% in monoculture and 45.5% in intercropping, while soybean yield increased by 17.7% and 17.9%, respectively, compared to uninoculated control. Land equivalent ratio (LER) values ranged from 1.44 to 1.60, indicating more efficient land use under intercropping than monoculture. Phosphate fertilization did not significantly affect LER but moderately improved crop performance. These results highlight the potential of combining local AMF and intercropping systems to enhance crop productivity and support sustainable agricultural intensification in tidal swamp ecosystems.

1. Introduction

The development of sugar production in the last five years from 2017 to 2021 tended to fluctuate, but until 2021, local sugar production was still unable to meet all domestic sugar needs [1]. Expanding sugarcane plantations, the primary raw material for sugar, is one way to boost sugar production in Indonesia. South Sumatra is the fourth-largest sugarcane production center in Indonesia, after Central Java, Lampung, and East Java, and contributes approximately 4.33% to Indonesia's sugar production, with a sugarcane plantation area of approximately 28,200 hectares in 2021[2]. Tidal swamp land is found in abundance in South Sumatra, around 3.02 million hectares, and has not been optimally utilized due to low land productivity and planting intensity, because its mainly the pyrite layer or sulfidic material which, when oxidized, will cause an acidification process and be toxic to plants [3, 4]. Technical problems in tidal land can be overcome, one of which is by implementing a location-specific agricultural technology system such as the application of a saturated soil cultivation (SSC) system and the use of local microorganisms such as arbuscular mycorrhizal fungi

(AMF) so that tidal land can become productive land and sugarcane plants can produce optimally.

Naturally, local microorganisms that form a symbiotic relationship with plant roots help plants absorb nutrients, especially phosphorus. Spores of arbuscular mycorrhizal fungi, *Acaulospora* and *Glomus*, were found on the roots of 2- month-old corn plants planted in tidal land [5]. Inoculation of arbuscular mycorrhizal fungi of the *Glomus* sp and *Acaulospora* sp types from corn host plants showed better vegetative growth of sugarcane plants compared to uninoculated sugarcane plants [6]. Inoculation of mixed mycorrhizal fungi Glomus and Acaulospora can increase the absorption of N and P nutrients in rubber plants (*Hevea brassiliensis* Muell. Arg.) that are stressed by drought [7]. Inoculation of mycorrhizal fungi increases the absorption of N, P and K nutrients in mung bean plants (*Phaseolus radiatus* L.) on ultisol soil [8]. The application of P fertilizer is crucial for increasing production. The use of AMF (Anti-Macronutrient Fertilizer) is one way to utilize soil P, which is abundant in tidal areas. AMF can help its host absorb P, which is an immobile nutrient in the soil.

Similar to sugarcane, soybeans are a secondary crop whose demand continues to increase annually. Indonesia's national soybean demand in 2021 reached 2.7 million tons, while national soybean production was only 200,000 tons per year, with an average productivity of only 1.56 tons per hectare. Efforts to increase soybean planting area include intercropping with other, longer-term crops, such as sugarcane. Intercropping is a cropping pattern that can increase land productivity. The advantages of intercropping include efficient land use, reduced weed populations, and increased yields. The overall land equivalency value between sugarcane and soybeans is greater than one, making intercropping more efficient and productive than monoculture [9]. The aim of this study was to determine the effect of AMF inoculant and several doses of phosphate fertilizer and their interaction on the growth and productivity of sugarcane-soybeans and also to determine the land efficiency of the sugarcane-soybean intercropping pattern.

2. Materials and Methods

2.1 Time and Place

The research was conducted for eight months, from January to October 2022, beginning with a two-month sugarcane nursery. This research was conducted in the tidal flats of Mulyasari Village, Tanjung Lago District, Banyuasin Regency, South Sumatra, at an altitude of 63 meters above sea level. Measurements of AMF colonization observation parameters and calculation of yield components were conducted at the Plant Ecology Laboratory. Chlorophyll analysis and drying of plant biomass were conducted at the Plant Physiology Laboratory, Department of Agricultural Cultivation, Sriwijaya University. Leaf nutrient analysis was conducted at the Soil, Plant, and Fertilizer Testing Laboratory, AGH, IPB.

2.2 Tools and materials

The materials used in the study were corn-derived arbuscular mycorrhizal fungi inoculants, inorganic fertilizers in the form of nitrogen (46% N), phosphate (36% P_2O_5), potassium (60% K_2O), *Tanggamus* soybean seeds, PS 862 sugarcane seeds, agricultural lime, and pest control materials. The tools used included soil cultivation tools, pest control tools, a knapsack sprayer, a water pump, an analytical balance, an oven, calipers, a refractometer, saccharin, and stationery.

The study used a Randomized Complete Block Design (RKLT) with two factors and three replications. The first factor is the provision of AMF inoculant (without inoculation, and inoculation from corn host plants) and the second factor is the dose of P fertilizer (0, 36, 72, 108 kg ha-1 P_2O_5), each carried out with a water-saturated cultivation system for 2 months since planting, so that there are 8 treatments with 3 replications with a total of 24 treatment plots, to calculate the LER, experiments were carried out in sugarcane and soybean monocultures so that there are a total of 72 treatment plots.

2.3 Research procedures

2.3.1. Sugarcane-Soybean Monoculture and Intercropping Systems

Soil amelioration was performed by applying dolomite and manure two weeks before planting. The plots were then fertilized with 2 tons of dolomite and manure each per hectare. The cultivation system used was a water-saturated cultivation system with plots measuring 4 m x 3 m, with SSC channels measuring 30 cm wide and 30 cm deep. In the sugarcane-soybean intercropping system, sugarcane was planted using single-bud planting (single-bud planting) with a center-to-center spacing of 135 cm and a row spacing of 50 cm, with one seedling per row. A corn-derived AMF inoculant was applied to the planting hole at a rate of 5 g per plant.

Soybean seeds were planted between each sugarcane plant in 3 rows and one row on each edge of the plot. Soybean seeds were planted 7 days after the sugarcane was planted using a ditch method with a hole depth of 2 cm. Each hole was filled with two seeds per planting hole with a distance of 40 x 15 cm, and an application of AMF inoculum from corn of 5 g/plant was given at the same time as the seeds were planted and the planting hole was covered with rice husk charcoal. Plot preparation in the sugarcane and soybean monoculture system was the same as the sugarcane-soybean intercropping system

2.3.2. Fertilization Application in Monoculture and Intercropping of Sugarcane-Soybeans

The dosage of phosphate fertilizer for sugarcane and soybean plants in both monoculture and intercropping according to the treatment is 0, 36, 72 and 108 kg/ha P_2O_5. Sugarcane fertilization (monoculture and intercropping) is given with a standard fertilizer dose of 400 kg/ha of nitrogen fertilizer (46% N), and 150 kg/ha of potassium fertilizer (60% K_2O). Sugarcane fertilization is done twice, namely the first fertilization is done at planting with 1/3 of the dose of nitrogen fertilizer, one dose of phosphorus according to the treatment and 1/3 of the dose of potassium fertilizer and the second fertilization is given two months after the first fertilization with the remaining dose, then hilling is done to a height of 5-10 cm. Fertilization of soybean plants (monoculture and intercropping) with a standard fertilizer dose of 10 g/l of nitrogen fertilizer water (46% N) with a spray volume of 400 l/ha which is given by spraying at the age of 2, 4 and 6 MST and 100 kg/ha of potassium fertilizer (60% K_2O) at the time of planting.

Observations on sugarcane (monoculture and intercropping) were conducted monthly starting from the first month after planting (MAP). Observed variables were plant height, number of leaves, number of shoots per meter of plot and number of stems per meter of plot, number of stem segments, stem diameter, biomass dry weight, analysis of leaf N, P, and K nutrient content, N, P, and K uptake at 6 MAP, as well as sugarcane production per hectare and the percentage of AMF colonization. Sugarcane plant height was measured from the soil surface to the tip of the shrimp claw. The number of fully opened leaves on all sample plants was recorded. The number of shoots per meter of segment was carried out on the sample segment (the segment used as an example is the segment located in the middle of the plot (one plot consists of three segments). The number of stem segments was carried out on sample plants used for plant height observations. Observations on the number of stem segments were carried out from the lowest segment to the segment before the growing point. The stem diameter was observed at the third segment from the bottom of the stem using a caliper with millimeter units. The dry weight of biomass was observed at 6 MAP by removing one plant, then separated into leaves, stems and roots. The dry weight of biomass was dried in the sun and then weighed after the roots, stems, and leaves were oven-dried for 24 hours and a temperature of 105°C. Analysis of the nutrient content of N, P, K leaves and nutrient absorption of N, P, K leaves at the age of 6 MAP and land equivalence ratio (LER).

Based on the results of each type of plant in intercropping and monoculture, the land equivalence ratio can be obtained as follows:

$$LER = \frac{YPts}{YPm} + \frac{YTts}{YTm}$$

YPts = yield of intercropped secondary crops.
YTts = yield of intercropped sugarcane.
YPm = yield of monoculture secondary crops.
YTm = yield of monoculture sugarcane [10].

The obtained data were analyzed using analysis of variance (ANOVA) if there was a significant effect, followed by the DMRT test at a 5% significance level. The observation data were processed using the STAR (Statistical Tool for Agricultural Research) application software and Microsoft Excel version 2021.

3. Results and Discussion

3.1 Characteristics of Sugarcane Growth and Productivity (Monoculture and Intercropping)

The application of inoculants to intercropped sugarcane significantly increased plant height, leaf number, and tiller number. The P dose significantly increased plant height (Table 3.1.). Leaf formation is necessary for the photosynthesis process to form biomass and glucose in the sugarcane stems. The number of tillers in monoculture sugarcane treated with AMF inoculants was greater than that in intercropped sugarcane.

Table 3.1. Plant height, number of leaves and number of sugarcane tillers at 5 MAP age.

Treatment	Monoculture sugarcane			Intercropping sugarcane		
	Plant height (cm)	Number of leaves	Number of offspring	Plant height (cm)	Number of leaves	Number of offspring
AMF inoculant						
No-inoculant	254.33b	8.5b	5.3	263.54b	10.5	2.7
inoculant added	297.76a	9.5a	7.1	286.46a	10.7	3.2
P_2O_5 Doses						
0 kg P_2O_5	261.19	10.8a	4.6	268.79ab	10.1	3.2
36 kg P_2O_5	304.71	8.4c	7.3	255.88b	10.1	3.0
72 kg P_2O_5	263.98	7.9c	5.7	285.96a	10.8	3.7
108 kg P_2O_5	274.31	8.9b	7.3	289.38a	11.5	2.0

Description: numbers followed by the same letter in the same column are not significantly different at the 5% level using the DMRT test.

The inoculant treatment and P dose significantly increased the stem diameter and stem length of monoculture sugarcane (Table 3.2). The stem diameter, stem length, and stem weight per meter of monoculture sugarcane were lower compared to intercropped sugarcane. This may be because the photosynthesis results in monoculture sugarcane are largely used to form the number of tillers, thus affecting the stem diameter, stem length, and stem weight per meter of the mother plant. Soil saturation for 2 months with AMF inoculation resulted in higher stem diameter, stem length, and stem weight per meter compared to the uninoculated soil. This is thought to be because AMF inoculation can increase the number of leaves so that the photosynthesis process occurs optimally, supported by the availability of sufficient water and sunlight, thus increasing the stem diameter, stem length, and stem weight per meter.

Table 3.2. Stem diameter, stem length and sugarcane stem weight per meter.

Treatment	Monoculture sugarcane			Intercropping sugarcane		
	Stem diameter (cm)	Stem length (cm)	Stem weight/m (g)	Stem diameter (cm)	Stem length (cm)	Stem weight/m (g)
AMF inoculant						
No-inoculant	2.68b	129.40b	0.522	2.75	132.00	0.610
inoculant added	2.83a	172.58a	0.597	2.74	138.38	0.693
P_2O_5 doses						
0 kg P_2O_5	2.95a	137.13b	0.623	2.72	141.00	0.590
36 kg P_2O_5	2.50c	163.11a	0.502	2.58	126.42	0.652
72 kg P_2O_5	2.80a	155.83a	0.502	2.85	142.83	0.657
108 kg P_2O_5	2.77b	147.89a	0.610	2.83	130.50	0.707

Description: numbers followed by the same letter in the same column are not significantly different at the 5% level using the DMRT test.

The inoculant treatment significantly increased the total chlorophyll content (Table 3.3). This is thought to be due to the colonization of the AMF by the plant, and the availability of sufficient chlorophyll content. Drought stress can reduce chlorophyll concentration, especially in plants not inoculated with AMF. This can be seen in some grape leaves that appear to wilt and fall off after 7 days of stopping watering. Plants that lack water will induce pigment degradation, which can increase the regulation of chlorophyllase activity and downregulate enzymes involved in chlorophyll biosynthesis. This increase in chlorophyll is also supported by an increase in plant height and number of leaves, which impacts the increase in stem diameter, stem length, and stem weight per meter.

Inoculant treatment increased the number of plant stomata, although it did not show a statistically significant effect compared to no inoculant treatment. This is suspected because the increased number of stomata likely increases stomatal conductance, followed by an increase in leaf surface area. AMF inoculation significantly increased plant height, leaf number, chlorophyll content, and biomass in both sugarcane and soybean. This improvement is likely due to enhanced nutrient and water uptake through extensive hyphal networks that expand the effective root absorption zone. AMF can mobilize poorly-available phosphorus under acidic wetland conditions through organic acid secretion and phosphatase activity, improving plant access to immobile P pools. Enhanced chlorophyll content in inoculated plants indicates increased photosynthetic capacity, which aligns with reports that AMF symbiosis increases leaf chlorophyll by improving nitrogen assimilation and maintaining stomatal performance during moisture stress. The higher stomatal density observed in inoculated plants suggests improved gaseous exchange efficiency, supporting greater carbon assimilation for biomass production According to research [11] mycorrhizal grapevines exhibit higher stomatal conductance, higher transpiration and photosynthesis rates, and lower intercellular CO_2 concentrations compared to uninoculated AMF-inoculated grapevines experiencing water stress. This suggests that AMF colonization can enhance photosynthesis by increasing the plant's gas exchange capacity under water stress. AMF are considered metabolic sinks for photosynthate mobilization to plant roots, thus signaling greater photosynthetic activity. Decreased stomatal conductance indicates that the plant is experiencing stress, which will affect its metabolic rate, resulting in a decrease in photosynthesis rate [12].

Table 3.3 Total chlorophyll, number of stomata and leaf area of sugarcane in sugarcane-soybean intercropping

Treatment	Total chlorophyll (mg/l)	Number of stomata/cm^2	Leaf area (cm^2)
AMF inoculant			
No-inoculant	4.48b	45.4	581.06
inoculant added	6.35a	47.9	686.96
P2O5 Doses			
0 kg P2O5	6.02	48.2	578.45
36 kg P2O5	4.70	46.1	560.36
72 kg P2O5	5.33	46.6	665.88
108 kg P2O5	5.59	45.9	731.34

Description: Means followed by the same letter in the same column are not significantly different at the 5% level using the DMRT test.

The nutrient content and nutrient absorption of N. P. K in sugarcane leaves in sugarcane-soybean intercropping increased with the provision of inoculants compared to without inoculants (Table 3.4). Inoculation of AMF on sugarcane roots will increase the absorption of N. P and K nutrients. This is thought to be due to the mutualistic symbiosis between plants and AMF, thereby increasing water absorption. P nutrients and other nutrients needed by plants needed by plants for the photosynthesis process. The highest levels of N, P, and K in sugarcane leaves were found in the AMF inoculant treatment, with N (0.89%), P (0.16%), and K (1.61%). Compared with the nutrient adequacy values for sugarcane (0.05% P and 1.00-1.6% K), the leaf P and K levels in the sugarcane analysis were within the sufficient range. Meanwhile, N levels were still below the sufficient range (1.5%). P levels at doses of 0 kg P2O5 and 36 kg P2O5 indicated that leaf P levels were within the sufficient range. This is likely due to the very high total P content in the soil.

Tabel 3.4 Levels and absorption of N, P, K nutrients in sugarcane leaves in sugarcane-soybean intercropping

Treatment	Leaf nutrient content (%)			Leaf nutrient absorption (g/plant)		
	N	P	K	N	P	K
AMF inoculant						
No-inoculant	0.88	0.15	1.51	1.19	0.21	2.02
inoculant added	0.89	0.16	1.61	1.70	0.30	3.02
P_2O_5 Doses						
0 kg P_2O_5	0.90	0.14	1.73	1.18	0.18	2.24
36 kg P_2O_5	0.92	0.13	1.60	0.98	0.15	1.75
72 kg P_2O_5	0.89	0.17	1.61	1.91	0.37	3.52
108 kg P_2O_5	0.83	0.16	1.30	1.69	0.31	2.58

Description: numbers followed by the same letter in the same column are not significantly different at the 5% level using the DMRT test.

N, P, and K uptake were higher in AMF-treated plants, indicating more efficient nutrient acquisition. This aligns with the role of AMF in enhancing root surface area and facilitating ion transport through extraradical hyphae. In saturated tidal soils, where P solubility is limited due to Fe-Al bonding, AMF likely improve P availability by altering rhizosphere chemistry and increasing the expression of high-affinity P transporters in host roots. Similar results were reported in upland crops under waterlogged conditions, suggesting that AMF symbiosis may help maintain nutrient supply under suboptimal aeration.

The AMF inoculant significantly increased sugarcane root colonization in the form of vesicle and arbuscular structures. The P2O5 dose significantly increased AMF root colonization in the arbuscular form (Table 3.5).

Tabel 3.5 Colonization of sugarcane roots by AMF in sugarcane-soybean intercropping

Treatment	AMF Colonization Percentage (%)		
	Internal hyphae	Vesicles	Arbuscular
AMF inoculant			
No-inoculant	97.00	28.75b	34.58a
inoculant added	99.00	10.33a	22.50b
P_2O_5 Doses			
0 kg P_2O_5	98.33	20.00	25.33b
36 kg P_2O_5	98.50	22.33	28.83ab
72 kg P_2O_5	97.67	22.17	43.17a
108 kg P_2O_5	97.50	13.67	16.83b

Description: numbers followed by the same letter in the same column are not significantly different at the 5% level using the DMRT test.

The increase in internal hyphal colonization in the AMF inoculant treatment ranged from 99% to produce wider roots, resulting in a larger root volume, as seen from the increase in root dry weight, thereby increasing the water and nutrient absorption zone and ultimately impacting the increase in shoot dry weight and production. According to [13] the administration of mycorrhizal inoculants significantly increased the percentage of colonization and distribution of hyphae, both internal and external hyphae, in the root cortex of plants. External hyphae of AMF are extensions of the root system to absorb mineral nutrients from the soil and help release P, Cu, and Zn nutrients so that they are available to plants. While nitrogen is absorbed by external hyphae in the form of NH4 or NO3 and in the form of amino acids.

3.2 Sugarcane Productivity and Land Use Efficiency

The results of the study showed that the interaction between mycorrhizal application and P_2O_5 dosage did not significantly affect the productivity characteristics of sugarcane. However, AMF inoculant significantly increased the productivity of sugarcane and soybeans in both intercropping and monoculture systems. AMF inoculant and P_2O_5 dosage did not significantly affect the land equivalence ratio (LER) (Table 3.6). The application of AMF inoculant was able to increase the production of sugarcane and soybean monocultures by approximately 86.5% and 17.7%, respectively. Meanwhile, in intercropping, there was an increase in sugarcane and soybean production by approximately 45.4% and 17.9% compared to without AMF inoculant. The application of phosphate fertilizer with a dosage of 36 kg P2O5 was able to increase the production of intercropped sugarcane (7.07%) and monoculture sugarcane (23.01%) compared to a dosage of 72 kg P_2O_5. This is thought to be because in monoculture cultivation there is no competition between sugarcane as the main crop and soybeans, especially in terms of sunlight.

AMF inoculation increased sugarcane yield by 45.5% and soybean yield by 17.9% under intercropping, demonstrating the agronomic value of symbiosis in multi-species systems. LER values ranged from 1.44 to 1.60, indicating a 44–60% land advantage over monoculture. These results are consistent with earlier reports on sugarcane-soybean systems, where LER values of 1.2–2.2 have been documented depending on variety and management conditions. The positive LER values suggest complementary resource use, where soybeans benefit from early canopy light availability, while sugarcane gains from improved soil biological activity facilitated by legumes and AMF. An LER value of more than indicates that the sugarcane-soybean intercropping system can increase land productivity compared to monoculture. This indicates that soybeans can be intercropped with sugarcane during early growth. This is in line with previous research that intercropping patterns are more efficient and productive than monoculture with the highest LER between sugarcane variety VMC 76-16 intercropping with soybean variety Kaba at 2.21 [14].

In a monoculture system with AMF inoculant treatment, sugarcane production was 86.7% higher than that without inoculant. AMF inoculant treatment in sugarcane-soybean intercropping increased sugarcane production by approximately 45.48%. This is likely due to the PS 862 variety being an early-mid-ripening variety, whose maturity and biomass production are highly dependent on the season. Optimal sugarcane productivity can be achieved by using varieties suited to the land topology [15].

Tabel 3.6 Productivity of sugarcane and soybean in sugarcane-soybean intercropping and land equivalence ratio value

Treatment	Productivity (ton/ha)				Land Equivalence Ratio (LER)
	Monoculture		Intercropping		
	Sugarcane	Soybean	Sugarcane	Soybean	
AMF inoculant					
No-inoculant	47.08b	3.43b	37.79b	2.75b	1.60
inoculant added	87.85a	4.04a	54.98a	3.28a	1.44
P_2O_5 Doses					
0 kg P_2O_5	58.46	3.49c	41.53	2.86b	1.53
36 kg P_2O_5	73.12	3.76b	49.31	3.03a	1.48
72 kg P_2O_5	59.44	4.05a	46.05	3.13a	1.55
108 kg P_2O_5	78.85	3.65bc	48.64	3.02ab	1.44

Description: numbers followed by the same letter in the same column are not significantly different at the 5% level using the DMRT test.

4. Conclusion

The interaction between mycorrhizal application and P dosage did not show a significant difference in the productivity characteristics of sugarcane plants. However, AMF inoculants showed a significant effect on the productivity of sugarcane and soybean plants, both in intercropping and monoculture systems. Meanwhile, AMF inoculants and P2O5 dosages did not show a significant effect on the land equivalence ratio (LER) value. In the monoculture system, saturation 2 months after planting with AMF inoculant treatment resulted in a significant increase in sugarcane production, namely 86.7% when compared to plants that were not given inoculants. Sugarcane-soybean intercropping. AMF inoculant treatment increased sugarcane production by approximately 45.48% compared to plants that were not inoculated. The results showed that the use of AMF inoculants contributed significantly to increasing sugarcane production, both in monoculture and sugarcane-soybean intercropping systems. Sugarcane- soybean intercropping can improve land utilization compared to monoculture with LER values ranging from 1.44-1.60.

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