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Research Article

Sugarcane-raya intercropping: A promising option to sustain yield and enhance farm profitability

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ABSTRACT

Sugarcane is a long-duration and slow-growing crop, which permits the opportunity to cultivate a short-duration crop in the same field during the same season. In this regard, intercropping of a mustard species "Super raya" can be the best option to enhance economic returns and improve overall land productivity. Therefore, a field trial was conducted to evaluate the effect of planting times of sugarcane and planting geometries of raya at Sugarcane Research Station, Khanpur, Rahim Yar Khan, Punjab, Pakistan. Experimental treatments were composed of two planting times of sugarcane (PD1=September 10, 2023, and PD2=October 10, 2023) and planting geometries of raya (S-1R=single row raya, S-2R=double row raya, and S-3R=triple row raya) intercropped within sugarcane. Sole sugarcane (S-Cn) and sole raya (R-3R) were also included as control treatments. Results of the current study showed that sole raya and sole sugarcane crops showed the maximum yields of 142.6 tons ha-1 (PD1) and 1.8 tons ha-1, respectively, as compared to other tested arrangements. Double row planting geometry of raya within September sugarcane also exhibited greater yield of 134.6 tons' ha-1 and 1.53 tons ha-1 for sugarcane and raya, respectively. This double row plant geometry within September-sown sugarcane also showed a higher benefit-cost ratio (32.4%) and land equivalent ratio (2.27%) attributed to a lower yield reduction ratio (0.6), greater yield stability index (0.94), and land equivalent ratio (1.80) under this treatment. In conclusion, double-row planting of raya within September-sown sugarcane can be recommended as a profitable agronomic practice for increasing land use efficiency and farm income in arid agro-climatic regions.

Keywords: Sustainability; sugarcane; super raya; farm income.

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INTRODUCTION

Global increasing demand for food and water poses significant challenges to the sustainability of our planet (Herte, 2015), particularly as the population continues to increase, putting additional strain on food resources (Fróna et al., 2019). The relationship between climate change and agriculture is evident, as favorable weather conditions can enhance crop yields, while shift in temperature and rainfall patterns can adversely affects production (Xu et al., 2025; Khalifa, 2025). In this context, Pakistan stands out as a country facing significant challenges due to its high levels of climate variability and rapid population growth, which necessitate increased production of cereals, sugar, oilseed, and other food crops (Abbas et al., 2025). Sugarcane serves as a valuable source for producing sugar and other by-products, accounting for approximately 80% of the world's total sugar output (de Matos et al., 2020; Goldemberg et al., 2018). As a result, it has become a globally important economic and cash crop, with Pakistan ranking fifth in its production. Furthermore, this ranking continues to rise steadily (FAO, 2024). Punjab Province is the primary.

sugarcane-growing region, contributing more than half of the country's total sugarcane production in Pakistan (Raza and Amir, 2021). However, recent challenges, including competition with other crops, climatic shift, high temperature, and low rainfall, have badly affected yield (Ahmed et al., 2019; Hussain et al., 2018). Shifting sowing time can be an effective agronomic practice that can enhance sugarcane performance under changing climate scenarios (Singh et al., 2019). Adhikari et al. (2025) reported that sowing sugarcane at the right time improves germination, increases the number of tillers, plant growth, yield, and sugar recovery.

An intercropping is recognized as a key agronomic practice for maximizing resource-use efficiency and strengthening food security (Maitra et al., 2021; Fung et al., 2019). This practice boosts overall food production by making more efficient use of land, water, and nutrients (Mala et al., 2020). It strengthens crop resilience against pests, diseases, and the effects of climate change (Maitra et al., 2021; Zhao et al., 2024). Intercropping is a low-input strategy that promotes crop diversification, caters to farmers' needs, and contributes to the national economy (Kugbe et al., 2018). The combination of short-duration crops with sugarcane is increasingly utilized due to its numerous advantages (Shukla et al., 2017; Geetha and Tayade, 2023). Every year, Pakistan spends millions of dollars on importing edible oils (Hussain et al., 2023). Researchers and policymakers have been working for decades on developing self-sustaining cropping systems that are energy efficient and require minimal inputs, and this system expands the area of oilseed crops and productivity, addressing national goals to decrease reliance on edible oil imports (Zaidi et al., 2024, GOP, 2025).

Raya (*Brassica juncea*) is a significant oilseed crop primarily cultivated in Pakistan, yielding 40-42% oil with an erect plant type and high yield potential (Nadeem et al., 2019). It is considered a promising candidate for intercropping within sugarcane due to its short duration and compatibility with the crop’s growth pattern (Sanghera and Sharma, 2024). The initial growth of sugarcane shows a relatively slow growth rate and limited canopy cover (Khonghintaisong et al., 2021). Numerous studies have reported that an intercropping promotes the competition for essential inputs and the potential reduction in tillering during early stages (Wang et al., 2020; Raza et al., 2024). Competition significantly influences yield advantage in an intercropping system, with lower inter-species competition resulting in higher yield compared to intra-species competition (Yang et al., 2013). Global attention has been emerged on sugarcane-raya intercropping, but limited studies have explored the interspecific competition between two crops. Therefore, this study examined the effect of varying sowing times days to emergence, number of tillers, plant height and cane yield of sugarcane. Moreover, the study also examined the interspecific competition between raya and its competition with sugarcane, along with assessing the economic feasibility of an intercropping system that integrates both crops.

MATERIALS AND METHODS

Experimental site, soil and climate

A field experiment was conducted at the experimental area of Sugarcane Research Station, Khanpur (28.63° N, 70.65° E), during the autumn season 2023-24. The soil at the experimental site is brownish in color with a loamy texture. The chemical and physical characteristics of soil at the site are presented in Table (1). The climate of the experimental site is arid being characterized by hot summers and cold winters. The weather data, including daily maximum and minimum temperatures and rainfall, is presented in Figure (1).

Table 1. Chemical and physical characters of soil at experimental site.

Parameters	Initial	At harvest
Soil pH	8.50	8.50
Soil Electrical Conductivity (dS m^{-2})	3.70	3.60
Available Soil Nitrogen (mg kg^{-1})	78.5	77.1
Available Soil Phosphorus (mg kg^{-1})	7.60	7.80
Available Soil Potassium (mg kg^{-1})	225	230
Soil Organic Matter (%)	1.25	1.25

Note: Soil samples were collected from 0-30 cm soil depths.

Experimental setup and treatments

The experiment consisted of two factors, viz., Sugarcane planting time, i) 10 September 2023 and ii), 10 October 2023, and intercropping of mustard species “super raya” with various planting geometries of raya (S-1R=single row raya, S-2R=double row raya, and S-3R=triple row raya) intercropped within sugarcane. Sole sugarcane (S-Cn) and sole raya

(R-3R) were also included as control treatments (Figure 2). A randomized complete block design under split plot arrangement with three replicates was used for the arrangement of the studied factors during the present study.

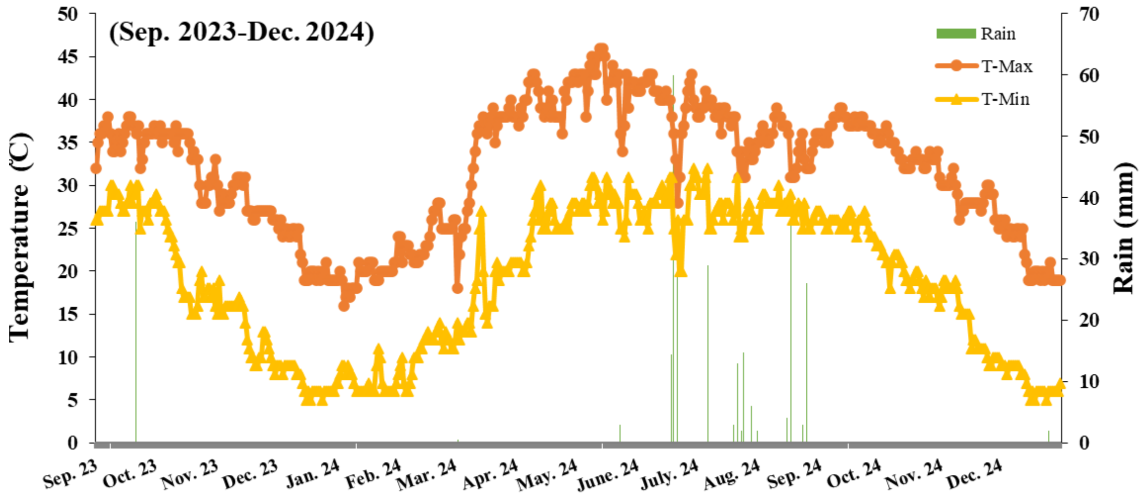

Figure 1. Weather data for the sugarcane-raya intercropping season from September 2023 to December 2024 in Khanpur, including average daily maximum and minimum temperature and rainfall.

Sugarcane planting times were arranged in main plots and planting geometries of raya in sub plots. Sugarcane was planted using a John Deere Planter with a four-foot row spacing on October 10. A John Deere Planter (Vintage John Derre, Model 290) is a rigid rectangular frame and vertically mounted row units, configured for either single- or double row plants, depending on the planned treatment and row-unit arrangements. Double rotary was applied between the rows, and the treatments were applied. All the phosphorus (112 kg ha-1), potash (112 kg ha-1) fertilizers, and half the nitrogen (84 kg ha-1 out of total 168 kg ha-1) fertilizers were applied as basal doses. The remaining nitrogen (84 kg ha-1) was divided in two equal splits, each of 42 kg ha-1.

Data recording protocols

Raya crop attributes

The key observations recorded following the standard protocols included time to start emergence, tillering, yield, and yield components. At maturity, the plant height of five tagged plants of raya was measured and averaged. Similarly, five siliques were randomly collected from each plot, and their length was measured and averaged. Moreover, the number of seeds of five randomly selected siliques was counted and averaged. All the plants were harvested, threshed, and their weight was recorded as the yield (tons ha-1).

Sugarcane crop attributes

Five plants were randomly tagged in each plot and their number of tillers were counted and mean was calculated. At harvest, the plant height of the tagged five plants was recorded and averaged. All the sugarcane plots were harvested and weighed to record the yield of the sugarcane into tons ha-1. Brix percentage was measured using a Brix hydrometer standardized at 20°C. Similarly, yield reduction ratio, yield stability index, land equivalent ratio, competitive ratio, agreesivity and benefit cost ratio were also calculated using standard protocols and procedures.

Yield reduction ratio (YRR) was also used for the quantification of yield reduction due to intercrop competition as compared to monoculture treatments. The equation (i) prescribed by Banik (1996) was used for measuring yield reduction ratio.

$$YRR = \frac{Yaa - Yab}{Yaa} \qquad (i)$$

Where, Yaa = sole yield of sugarcane, Yab = yield of sugarcane in intercrop, Ybb = sole yield of Raya, and Yba = yield of Raya in intercrop.

Yield stability index (YSI) was also measured in order to compare the changes in the yield of each crop by using the equation (ii) suggested by Karunarathna and Maduwanthi (2022).

$$YSI = \frac{Yab}{Yaa} \qquad (ii)$$

Land equivalent ratio (LER) was also calculated for the precise measurement of enhanced biological efficiency achieved through intercropping systems. It can be measured using the equation (iii) prescribed by Ghosh (2004).

$$LER = \frac{Yab}{Yaa} + \frac{Yba}{Ybb} \qquad (iii)$$

Competitive ratio (CR) was determined for real quantification of the relative competitiveness of one crop over another crop in the current intercropping system. It can be calculated using the equation (iv) suggested by Willey and Rao (1980).

$$CR = \frac{LERa}{LERb} \times \frac{Zba}{Zab} \qquad (iv)$$

Aggressivity (Aab) was also used calculated in order to quantify the relative competitive ability of sugarcane and raya crops cultivated simultaneously. In the current study, agressivity index was also measured using equation (v) introduced by Willey and Rao (1980).

$$Aab = \frac{Yab}{Yaa \times Zab} - \frac{Yba}{Ybb\ \times Zba} \qquad (v)$$

Net returns and benefit cost ratio (BCR) were calculated using the equation (vi) as described by CIMMYT (1988).

$$BCR = \frac{Benefits}{Cost} \qquad (vi)$$

Statistical analysis

The collected data were statistically analyzed using analysis of variance (ANOVA) technique (Steel et al., 1997). The honestly significant difference (HSD) test was utilized to compare the treatment means of the studied variables. Sigma Plot version 15 was also used for the graphical representation of the data.

RESULTS AND DISCUSSION

Emergence attributes of sugarcane crop

There was a significant effect of various planting times on the days to emergence of the sugarcane crop. The sugarcane planted on September 10th showed an early emergence, starting 20 days after planting, while sugarcane planted on October 10th showed late emergence, which started 30 days after planting during the study (Figures 3, 4). The maximum emergence percentage was 75% for Sept-sown (September 10th) and 50% for Oct-sown (October 10th), respectively. However, the super raya intercropped within the sugarcane with different planting geometries showed a non-significant effect on the days to emergence of the super raya (Figures 3, 4). Early emergence and a greater number of tillers by the September-sown sugarcane might be linked with the optimal range of temperature in September (Figure 1). The ideal temperature for sugarcane germination falls between 27-36 °C, with the most favorable range being around 30-32°C (Carvalho et al., 2023). In this study, the Sept-sown sugarcane experienced this temperature range resulting in better performance. Similar results were previously reported by Ganapati et al. (2016) that when the temperature decreased to 27 °C, germination rate declined and took a longer time to complete germination. Numerous previous studies have also reported that timely sowing combined with favorable soil moisture and temperature creates favorable conditions for germination and crop establishment (Ghaffar et al., 2022; Li, 2024). In contrast, delayed sowing reduces temperature during germination and ultimately delay emergence (Simamora et al., 2024). Our study revealed similar results as October-sown sugarcane showed late emergence due to lower temperature (Figures 1, 4). These findings suggested that timely planting of sugarcane is essential for optimal germination and timely crop stand establishment of the sugarcane.

Agronomic attributes of sugarcane crop

In the present study, various planting times and intercropping of various row planning geometries of super raya significantly affected the agronomic attributes, including the number of tillers per plant and the yield of the sugarcane crop. However, the effect of various planting times and intercropping of various row planning geometries of super raya was not significant on the plant height and Brix percentage of the sugarcane. Compared to Sept-sown sugarcane, Oct-sown significantly decreased the number of tillers per plant by 53.4% and yield by 28.7% respectively (Figure 5). Intercropping involves planting two crops simultaneously, which can create competition that may decrease the growth and yield of one or both crops (Takim, 2012). In this study, October-sown sugarcane produced fewer tillers when intercropped with raya compared to the September-sown sugarcane (Figure 5). Sun et al (2024) reported that sowing the initial crop earlier generally allows it to establish itself more successfully, giving it a competitive advantage. In contrast, the late-planted crop may face challenges such as shading and limited resources, confirmed in our study (Figure 5). Among the various row planning geometries for sugarcane intercropping, the combination of sugarcane

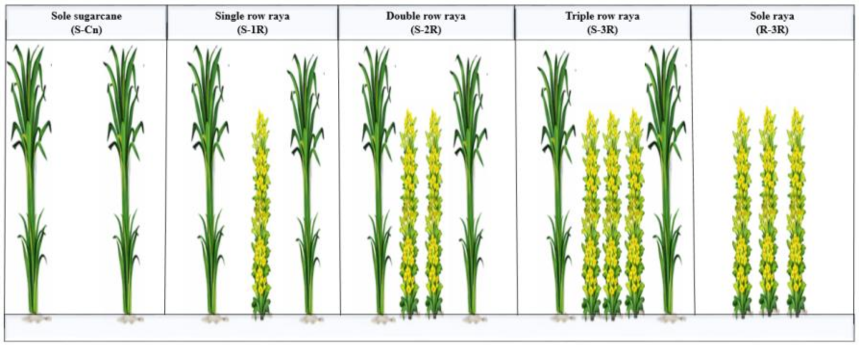

Figure 2. Arrangements of planting geometries of raya (S-1R=Single row raya, S-2R=Double row raya, and S-3R=Triple row raya) intercropped within sugarcane, Sole sugarcane (S-Cn) and Sole raya (R-3R) at the experimental site.

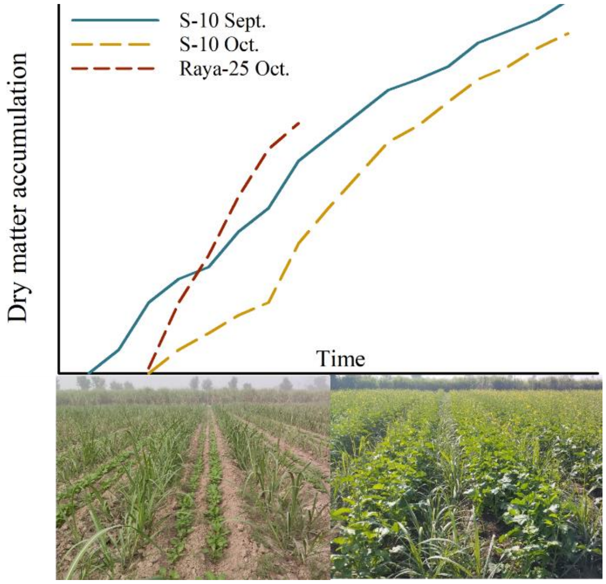

Figure 3. Response of planting time on the sugarcane-raya intercropping system. Sugarcane planted in September was nearly completed its emergence at the time of intercropping. In contrast, sugarcane planted in October faces competition with raya.

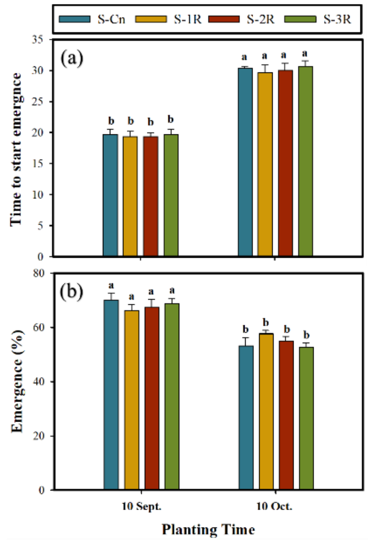

Figure 4. Effect of planting time on (a) time to strat emergence and (b) emergence percentage of sugarcane in sugarcane-raya intercropping system. Error bars represent standard error, and different letters mean a significant difference at $p < 0.05$. Single row raya (S-1R), Double row raya (S-2R), and Triple row raya (S-3R) within sugarcane and Sole sugarcane (S-Cn).

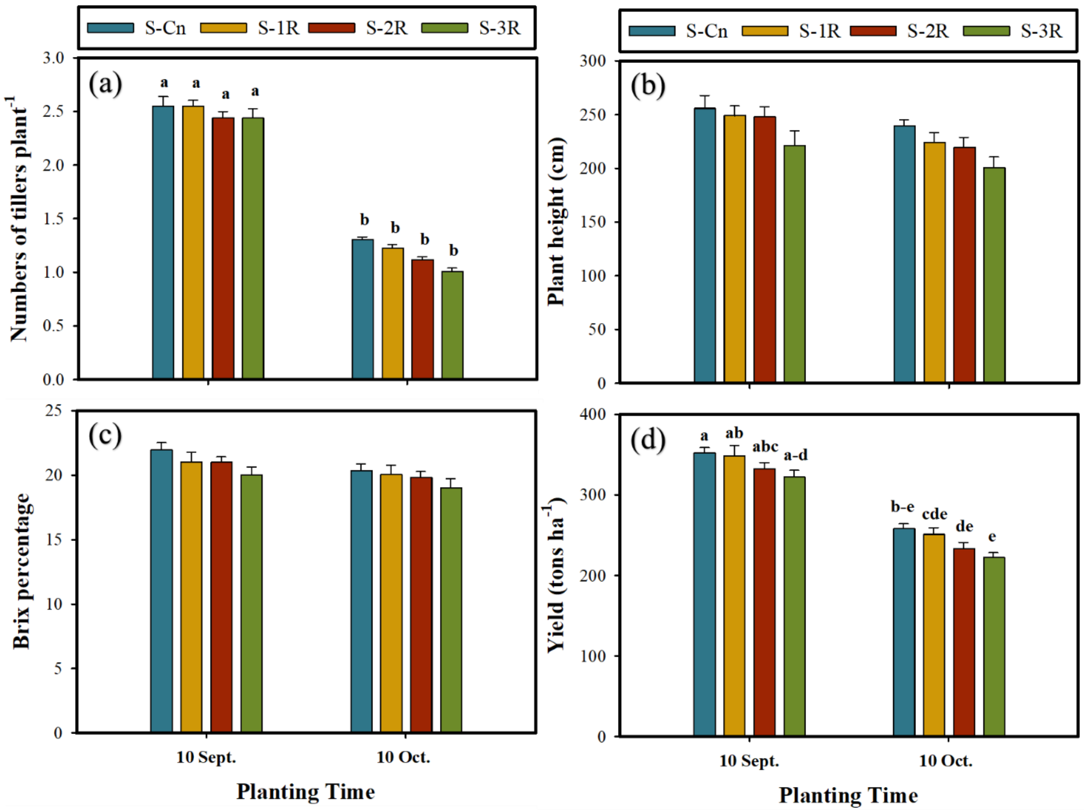

Figure 5. Effect of planting time on (a) number of tillers, (b) plant height, (c) brix percentage, and (d) yield of sugarcane in sugarcane-raya intercropping system. Error bars represent standard error, and different letters mean a significant difference at $p < 0.05$. Single row raya (S-1R), Double row raya (S-2R), and Triple row raya (S-3R) within sugarcane, and Sole sugarcane (S-Cn).

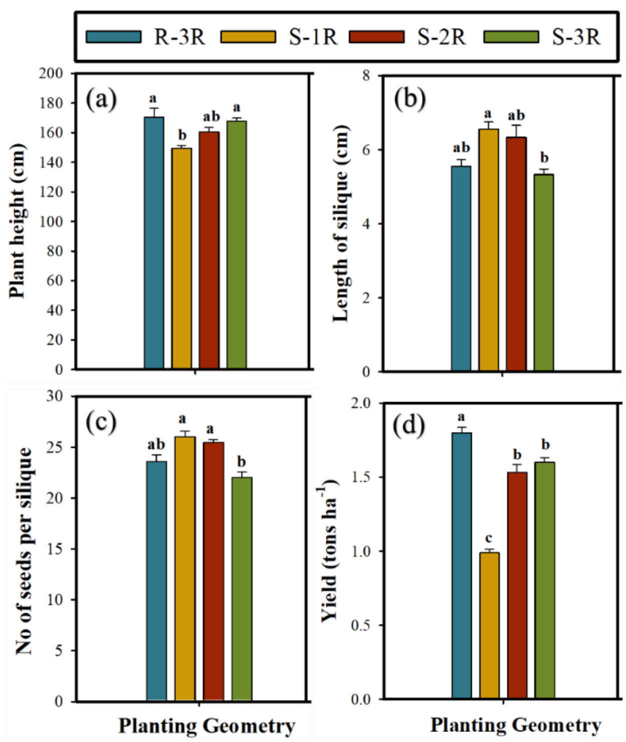

Figure 6. Effect of planting geometry on (a) plant height, (b) length of silique, (c) seed number, and (d) yield of sole and intercropped raya with sugarcane. Error bars represent standard error, and different letters mean a significant difference at $p < 0.05$. Single row raya (S-1R), Double row raya (S-2R), and Triple row raya (S-3R) within sugarcane; and Sole raya (R-3R).

with a single and double row of super raya showed the maximum number of tillers per plant and yield of the sugarcane crop during the current study (Figure 5). Greater number of tillers in single and double row planting was due to optimal planting geometry and better stand establishment of the sugarcane crop. Furthermore, optimal light interception and photosynthetic efficiency of the axillary buds sprouting, were also chief contributors behind more tillers per plant of the sugarcane crop. Similarly, more number of tillers and plant height were associated with enhanced nutrient and water uptake under single and double row planting as compared to three row planting. In the Sept-sown and Oct-sown sugarcane crop, the intercropping of super raya decreased the number of tillers per plant by 4.4% and 14.2% and cane yield by 5.6% and 9.6%, respectively, as compared to the sole sugarcane crop. A significant decrease in might be attributed to competition for natural resources and applied agricultural inputs (Anjaly and Ajith, 2025). However, better can yield might be attributed to more number of tillers and plant height in double row planting. Similarly, Kumar et al. (2024) has reported that number of tillers and plant height are directly linked with cane yield. These findings suggested that single and double row plantings within sugarcane was better option to maintained more number of tillers and can yield of the sugarcane.

Agronomic attributes of raya intercropped within sugarcane

Various planting geometries used for intercropping super raya within sugarcane significantly affected the various agronomic attributes of super raya. There was no significant effect of various planting geometries of super raya on the plant height, length of silique, and number of seeds per silique of the super raya during the present study (Figure 6). However, there was a significant effect of various planting geometries used for intercropping super raya on the yield of super raya. The sole raya crop showed the maximum yield of super raya. This higher yield of the sole raya crop might be associated with the more number of plants per unit area and number of siliques per plant as observed in the current study (Figure 6). Similar result was reported by Waseem et al. (2014), who found that raya sown on wider spacing produced higher yield due to length of silique, and number of seeds per silique. Double row planting exhibited the greater yield and yield components of the super raya due to low inter-row space, which led to sufficient light penetration and aeration and ultimately optimum growth and development and yield of the crop (Hussain et al., 2020; Afghan et al., 2024).

Competitive and economic analysis

A pronounced variation was recorded in the yield reduction ratio (YRR), yield stability index (YSI), land equivalent ratio (LER), agressivity (Aab) and benefit cost ratio (BCR) under sugarcane-raya intercropping (Table 2, 3). However, competitive ratio (CR) did not show significant differences by sugarcane-raya intercropping. In September-sown sugarcane, it was observed that sole sugarcane (S-Cn) showed no relative yield intercropping indices, thereby served as a baseline for comparison. Sugarcane-raya intercropping treatment i.e. S-1R, S-2R and S-3R exhibited lower YRR values, with a gradual rise in the YRR by increasing number of raya rows in September-sown sugarcane. (Table 2) This indicated that sugarcane experienced a minimum yield loss due intercropping, and can be considered as good compatibility between sugarcane and raya, thereby serve as resource efficient cropping system (Hollósy et al., 2023; Tang et al., 2024). Intercropping patterns within October-sown sugarcane also showed a marked increase in the YRR ranging from 2.77 to 13.93. The S-1R, S-2R and S-3R geometries showed similar lower YRR values, and decreased with a steady increase in the YRR by increasing number of raya rows. Similarly, these intercropping patterns also showed higher YSI, with a slightly decline in the YSI by increasing number of raya rows in September-sown sugarcane (Table 2). Higher YSI in this sugarcane-raya intercropping system highlighted an effectiveness of spatial arrangement in minimizing competition and maintained yield and resulting improved yield stability (Wang et al., 2024). Similar trend in the YSI was observed in the October-sown sugarcane, with lower YSI values when compared to September-sown sugarcane. In September-sown sugarcane, LER values consistently exceeded 1, which indicated that intercropping was more efficient than sole cropping (Table 3). In October-sown sugarcane, the LER values also showed similar trends and recorded greater than 1, which indicated that intercropping was more efficient than sole cropping's (Zhu et al., 2023). However, there was no significant difference in the LER between September-sown and October-sow sugarcane for all intercropping patterns. It was also observed that CR remained 1 across all intercropping treatments, which proposed that both crops i.e. sugarcane and raya have a balanced competition for each other in September- and October-sown sugarcane. The Aab values ranged from 2.47 to 3.22, which revealed that one crop has dominance in competition over the other (Table 3). These positive values of Aab indicated that sugarcane was the dominant crop over raya in the current intercropping. This point highlighted that sugarcane remained superior in capturing natural resources i.e. soil, water and nutrients as well as applied inputs in the present intercropping (Li et al., 2024). In October-sown sugarcane, the Aab decreased as compared to September-sown sugarcane. It indicated that dominance of

Table 2. Mean values of yield reductionratio, yield stability index and competitive ratio of the sugarcane-raya intercropping system.

Treatments		Yield reduction ratio	Yield stability index	Competitive ratio
September 10th	S-Cn	0.00	0.00	0.00
	S-1R	0.01d	0.99a	1.00a
	S-2R	0.06d	0.94bc	1.00a
	S-3R	0.09d	0.91cd	1.00a
October 10th	S-Cn	0.00	0.00	0.00
	S-1R	2.77c	0.97ab	1.00a
	S-2R	9.67b	0.90d	1.00a
	S-3R	13.93a	0.86e	1.00a

Mean with same letters indicating significant differences at $p<0.05$; Single row raya (S-1R), Double row raya (S-2R), and Triple row raya (S-3R) within sugarcane; Sole sugarcane (S-Cn) and Sole raya (R-3R).

Table 3. Mean values of land equivalent ratio (a: sugarcane and b: raya), agressivity and benefit cost ratio of the sugarcane-raya intercropping system.

Treatments		Land equivalent ratio (a)	Land equivalent ratio (b)	Agressivity (ab)	Benefit cost ratio
September 10th	S-Cn	0.00	0.00	0.00	1.95a
	S-1R	1.54a	1.54b	3.22a	1.92a
	S-2R	1.80a	1.80a	2.64b	1.96a
	S-3R	1.79a	1.81a	2.47c	1.92a
October 10th	S-Cn	0.00	0.00	0.00	1.44b
	S-1R	1.52b	1.52b	3.16a	1.48b
	S-2R	1.76a	1.76a	2.48c	1.44b
	S-3R	1.75a	1.75a	2.26d	1.43b

Mean with same letters indicating significant differences at $p<0.05$; Single row raya (S-1R), Double row raya (S-2R), and Triple row raya (S-3R) within sugarcane; Sole sugarcane (S-Cn) and Sole raya (R-3R).

component crop decreased by delaying sowing time of sugarcane. The BCR values were also comparable ranging from 1.92 to 1.96, with the maximum of 1.96 in the S-2R treatment in October-sown sugarcane (Table 3). In September-sown sugarcane, the BCR values ranging from 1.44 to 1.48 also decreased when compared to October-sown sugarcane. This higher BCR values by September-sown sugarcane were due to greater lower YRR, increased YSI, improved LER and ultimately enhanced yield of both crop sugarcane and raya. Overall, S-2R intercropping system showed greater lower YRR, increased YSI, improved LER and ultimately enhanced yield of both crop sugarcane and raya. It has also been reported that super raya + sugarcane intercropping increased land use efficiency by 35% and net returns by 28% in an arid climate (Ghaffar et al., 2022). Similarly, Shukla et al. (2022) also observed that super raya intercropping improved 25% higher gross income at the cost of 4% yield reduction in the sugarcane crop compared to a sole sugarcane crop. Overall, double row raya intercropping within September-sown sugarcane showed the highest benefit-cost ratio (32.4%) and land equivalent ratio (2.27%) when compared to October-sown sugarcane. The findings of the current study suggested that double row planting of raya within sugarcane can be the most effective strategy to maximize yields of both crops and enhance farm income in arid regions.

CONCLUSION

The results of the current study showed that sole super raya and sole sugarcane crops showed higher yields when compared to other tested arrangements. Double row raya planting within September-sown sugarcane exhibited the maximum yields of sugarcane and raya crops, benefit-cost ratio, and land equivalent ratio. This higher yield, benefit cost ratio, and land equivalent ratio were mainly attributed with lower yield reduction ratio and enhanced yield stability index by double row raya intercropping within September-sown sugarcane. In crux, double row raya planting within September-sown sugarcane can be recommended as a resource-efficient agronomic practice for maximizing land use efficiency and farm income in arid regions.

AUTHOR'S CONTRIBUTION

Taj Muhammad: Supervision, project administration and methodology. Tauqeer Qadir: Methodology; data curation and formal analysis. Muhammad Asif Jamal: Data curation, formal analysis, and preparation of initial draft. Diyan Haider: Manuscript review and editing, and data curation. Ijaz Hussain: Data curation and formal analysis. Saeed Ahmad: Data curation, formal analysis and revision.

FUNDING

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AVAILABILITY OF DATA AND MATERIAL

All data generated or analyzed during this study are available from the corresponding author upon reasonable request.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

The study was approved by the relevant institutional forum.

CONSENT FOR PUBLICATION

All authors have reviewed the manuscript and approved it for publication.

CONFLICT OF INTERESTS

The authors declare no conflict of interest.

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Not applicable.

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