



Plant Archives

Journal homepage: <http://www.plantarchives.org>

DOI Url : <https://doi.org/10.51470/PLANTARCHIVES.2026.v26.no.2.164>

SUSTAINABLE INTENSIFICATION OF SUGARCANE-BASED CROPPING SYSTEMS THROUGH ADDITIVE SWEET SORGHUM INTERCROPPING FOR BIOETHANOL PRODUCTION

Abhinandan Patil^{1*}, Samadhan Surwase¹, Pranali Dhekane¹, Ashok Kadlag¹,
Kakasaheb Konde¹ and Tushar Patil²

¹Vasantdada Sugar institute, Pune, Maharashtra, India

²PRAJ Industries Ltd., Pune, Maharashtra, India

*Corresponding author E-Mail: abhi9445patil@gmail.com

(Date of Receiving-04-06-2026; Date of Revision-24-07-2026; Date of Acceptance-11-08-2026)

The increasing global and national demand for renewable energy, particularly biofuels, has intensified the need to identify sustainable, high-yielding feedstock production systems without compromising food and fodder security. In this regard a project was initiated at Vasantdada Sugar Institute (VSI), Pune, during 2025–26 using a wide row spacing of 150 cm in sugarcane (variety Co 86032). Three sweet sorghum varieties— viz. Phule Amruta, Phule Vasundhara and Mega Sweet were evaluated under an additive intercropping system and compared with sole sugarcane. The study comprehensively assessed crop growth, yield attributes, juice quality, ethanol production potential and overall system economics.

The results demonstrated that intercropping had a moderate effect on sugarcane yield parameters, primarily due to interspecific competition during early growth stages. Sole sugarcane recorded the highest cane yield (132.00 t ha⁻¹), whereas, intercropped treatments showed comparatively lower yields. However, among intercropping treatment, the combination of sugarcane with sweet sorghum (var. Mega Sweet) performed the best, achieving a cane yield of 120.00 t ha⁻¹ along with improved growth attributes such as internode number and girth.

ABSTRACT

Importantly, the reduction in sugarcane yield was effectively compensated by the additional biomass and ethanol yield from sweet sorghum, making the system more productive on a per-unit-area basis. Sweet sorghum exhibited strong potential as a bioenergy crop, with ethanol yields ranging from 674.47 to 1267.50 lit ha⁻¹ across varieties. The Mega Sweet variety recorded the highest ethanol yield (1267.50 lit ha⁻¹), attributed to its higher biomass production, juice recovery and sugar content.

Economic analysis further highlighted the superiority of the intercropping system, from the farmers' perspective, the intercropping system achieved the highest gross income (Rs. 5,17,500 ha⁻¹) and net income (Rs. 4,08,500 ha⁻¹) compared to sole sugarcane and sole sweet sorghum cultivation. Intercropping provided an additional net income of Rs. 40,800 ha⁻¹ over sole sugarcane, demonstrating its economic advantage.

Overall, the study demonstrated that additive intercropping of sweet sorghum in wide-row sugarcane is a promising and economically viable production system for enhancing bioenergy feedstock availability, improving land-use efficiency, increasing ethanol productivity, and improving farmers' profitability while supporting sustainable renewable energy initiatives.

Key words: Sugarcane-sweet sorghum intercropping, yield, resource use efficiency, Bio-ethanol production, soil sustainability

Introduction

The rising demand for agricultural feedstock's for

biofuel production, combined with the limited availability of new land and the need to maintain food and feed

security, has made the adoption of inter-cropping systems essential. By integrating economically significant, short-duration biofuel crops with sugarcane on existing land, farmers—particularly marginal and smallholders—can sustain their sugarcane cultivation while, securing interim financial returns.

The escalating demand for biofuel feedstock's, coupled with the need to safeguard food and feed security on limited land, has made the adoption of inter-cropping systems essential. In sugarcane cultivation, the initial 90–120 days of growth are relatively slow, leaving significant space between rows unutilized. This window provides a strategic opportunity for companion cropping to maximize land-use efficiency.

Due to the wider row spacing and initial slow growth rate of sugarcane, there is ample scope for intercropping in sugarcane. The major objectives of intercropping are to produce an additional crop, to optimize the use of natural resources and to stabilize the yield of crops (Willey, 1979). The space available in between the wide row can be suitably used for growing component crops for increasing the total production per unit area.

With the introduction of high-tillering, high-yielding sugarcane varieties, it is now possible to adopt wider row spacing (150 cm) while, maintaining core cane productivity. This wider spacing serves as a critical agronomic tool, particularly in developing countries, as it permits the integration of economically important, short-duration biofuel crops without adversely affecting sugarcane yields. For small and marginal farmers, this system ensures interim financial returns and higher overall farm profitability.

Sweet sorghum has emerged as a promising target for sugar as well as lignocellulosic biofuel production. It has relatively low input requirements with ability to grow on marginal lands. (Mathur *et al.*, 2017).

To evaluate these potential economic gains and the feedstock supply for the biofuel industry, a joint field study was conducted by Praj Industries Ltd and the Vasantdada Sugar Institute at VSI's R & D farm (MS) Pune, India. The study specifically assessed the feasibility and compatibility of a “sweet sorghum-sugarcane” inter-

cropping model using an additive series approach.

Material and Methods

The current study was carried out during 2024-25 at the Research & Development farm of Vasantdada Sugar Institute, Manjari Bk., Pune, Maharashtra, India (latitude 18° 31' 34.323 N, longitude 73° 58' 28.563 E, and altitude 190 meters above mean sea level). As main crop sugarcane was grown with variety Co 86032 and three sweet sorghum varieties were compared viz. Phule Amruta, Phule Vasundhara and Mega Sweet.

Trial was laid out in augmented having plot size of 1000 m². The standard agronomic package of practices for main and intercrops were carried out independently which included regular interculturing, gap filling, thinning, weeding, and plant protection measures were applied as required. The information on yield, quality and the factors that contribute to it was documented during the entire growing season.

The juice extraction and fermentation experiments were conducted in the Department of Alcohol Technology and Biofuels, Vasantdada Sugar Institute (VSI), Pune, India. The total soluble solids (°Brix) of extracted juice and fermented wash were measured using a Brix hydrometer, while, specific gravity was determined using a specific gravity hydrometer. The pH of both raw juice and fermented wash was recorded using a calibrated digital pH meter.

Reducing sugars, total reducing sugars in raw juice, and residual sugar content in fermented wash were estimated following the standard Lane and Eynon titrimetric method (1923). The alcohol content of the fermented wash was determined using an Anton Paar densitometer.

Result and Discussion

The results demonstrated significant variation among different intercropping treatments of sugarcane with sweet sorghum varieties.

The yield-contributing parameters and yield (Table 1 and Graph 1) of sugarcane were significantly influenced by the different intercropping systems. Among the treatments, T₄ (sugarcane + sweet sorghum, var. Mega Sweet) recorded the highest single cane weight (1.71 kg),

Table 1: Single cane weight, cane & CCS yield of sugarcane as influenced by different treatment.

Treatment	Single cane wt. (kg)	Cane yield (t/ha)	CCS yield (t/ha)	Cane equivalent yield (t/ha)
T ₁ - Sole sugarcane	1.80	132.00	19.25	132.00
T ₂ - Sugarcane + Sweet sorghum (var. Phule Amruta)	1.69	94.39	12.65	108.36
T ₃ - Sugarcane + Sweet sorghum(var. Phule Vasundhara)	1.52	94.88	13.38	112.59
T ₄ - Sugarcane + Sweet sorghum (var. Mega Sweet)	1.71	120.00	17.06	147.86

Table 2: Juice quality and Ethanol yield of sweet sorghum as influenced by different treatment.

Treatment	JE	JB	BS	SRJB	SY	EY
T ₁ - Sole sugarcane	-	-	-	-	-	-
T ₂ - Sugarcane + Sweet sorghum (var. Phule Amruta)	55.00	18.20	75.00	20.40	1.51	674.47
T ₃ - Sugarcane + Sweet sorghum (var. Phule Vasundhara)	62.00	16.60	78.10	17.00	1.72	813.75
T ₄ - Sugarcane + Sweet sorghum (var. Mega Sweet)	62.00	17.30	78.10	17.00	2.67	1267.50
JE: Juice extraction (%); JB: juice Brix(0°); BS: Brix of syrup (0°); SRJB: Syrup recovery on Juice basis (%); SY: Syrup yield (t/ha); EY: Ethanol yield (lit/ha)						

Table 3: Soil Nutrient uptake as influenced by different intercropping system.

Treatment	Total Nutrient Applied (kg/ha)			Total Nutrient Uptake (kg/ha)		
	N	P	K	N	P	K
T ₁ - Sole sugarcane	545.00	93.9	737.45	221.41	48.00	351.00
T ₂ - Sugarcane + Sweet sorghum (var. Phule Amruta)	665.00	120.1	787.25	229.54	66.39	320.20
T ₃ - Sugarcane + Sweet sorghum (var. Phule Vasundhara)	665.00	120.1	787.25	260.93	71.38	347.84
T ₄ - Sugarcane + Sweet sorghum (var. Mega Sweet)	665.00	120.1	787.25	434.33	119.69	435.69

Table 4: Soil Nutrient balance as influenced by different intercropping system.

Treatment	Residual Soil Nutrient (kg/ha)			Nutrient Balance (kg/ha)		
	N	P	K	N	P	K
T ₁ - Sole sugarcane	245.00	42.00	305.00	78.59	3.90	81.45
T ₂ - Sugarcane + Sweet sorghum (var. Phule Amruta)	268.00	39.00	410.00	167.46	14.71	57.05
T ₃ - Sugarcane + Sweet sorghum (var. Phule Vasundhara)	288.00	35.00	392.00	116.07	13.72	47.41
T ₄ - Sugarcane + Sweet sorghum (var. Mega Sweet)	207.00	28.00	278.00	23.67	-27.59	73.56

cane yield (120.00 t ha⁻¹), and commercial cane sugar (CCS) yield (17.06 t ha⁻¹), significantly outperforming the remaining treatments. Similarly, the highest stripped plant yield (25.35 t ha⁻¹) and whole plant yield (39.00 t ha⁻¹) of the intercrop were also recorded under the sugarcane + sweet sorghum (var. Mega Sweet) intercropping system.

The appropriately selected intercrops in sugarcane improved resource-use efficiency and increased overall system productivity. The higher biomass production of sweet sorghum observed in the present study is also consistent with the findings of Almodares and Hadi (2009), who reported that sweet sorghum possesses high biomass accumulation and excellent adaptability under diverse agro-climatic conditions, making it a suitable crop for integrated production systems.

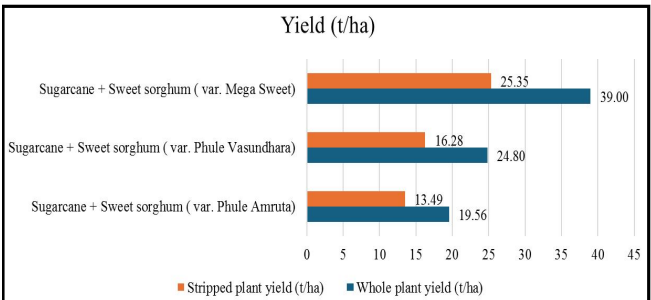


Fig. 1: Yield of sweet sorghum as influenced by different treatment.

In terms of juice quality and bioethanol potential (Table 2), Treatment T₂ recorded the highest juice °Brix (18.20) and syrup recovery (20.40%), indicating greater accumulation of soluble sugars and improved juice quality, which are essential for efficient bioethanol production (Mathur *et al.*, 2017; Oktem & Oktem, 2024). Higher °Brix reflects enhanced photosynthate accumulation and translocation of fermentable sugars into the stalk. However, T₄ produced the highest syrup yield (2.67 t ha⁻¹) and ethanol yield (1267.50 L ha⁻¹), suggesting that ethanol productivity depends not only on sugar concentration but also on the total juice and biomass yield per unit area (Rooney *et al.*, 2014; Oktem & Oktem, 2024). The comparable juice extraction efficiency (62.00%) observed

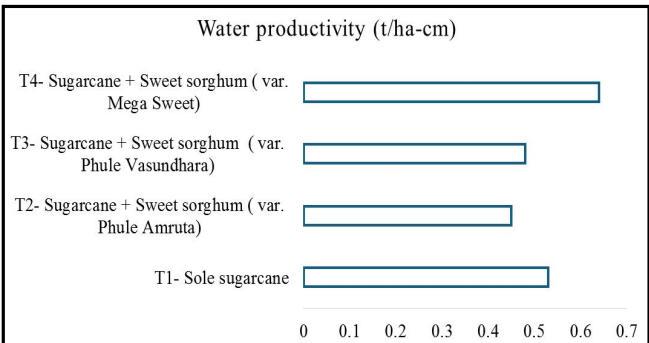


Fig. 2: Crop Water Productivity as influenced by different treatment.

Table 5: Comparative ethanol generation from different cropping systems (juice to ethanol).

Cropping system	Sole Sugarcane	Sole Sweet Sorghum	Sugarcane + Sweet Sorghum
Crop Cycle Duration	12 Months	4 Months	12 Months
Whole Green Biomass (t/ha)	-	47.00	39.00
Stripped Biomass yield (t/ha) (65%)	-	30.55	25.35
Cane yield (t/ha)	132.00	-	120.00
Ethanol Yield (lit/ton of cane)	75.00	50.00	50.00
Ethanol Yield (lit/ha)	9900.00	1527.50	10267.50

in T_3 and T_4 indicates better juice recovery from stalks, thereby increasing the availability of fermentable sugars for syrup preparation and ethanol production. These findings demonstrate that while T_2 enhanced juice quality, T_4 was more effective in maximizing syrup and ethanol yield because of its superior overall biomass and juice productivity, making it a more suitable treatment for commercial bioethanol production.

Date showed in Graph 2 indicated, sole sugarcane (T_1) recorded the highest cane yield (132.0 t/ha), but with moderate water productivity (0.53). Among intercropping systems, yield of sugarcane decreased, but sweet sorghum contributed additional biomass. T_4 (Sugarcane + Mega Sweet) performed best among intercrops with highest total yield and maximum water productivity (0.64), indicating better resource use efficiency. Overall, T_4 was the most efficient system despite lower cane yield than sole sugarcane. This might be due to more efficient utilization of available resources through complementary use of water, nutrients, and solar radiation (Raseduzzaman & Jensen, 2017). Improved resource complementarity and greater biomass production in T_4 enhanced overall system efficiency despite a slight reduction in cane yield. These findings suggest that sugarcane–sweet sorghum intercropping, particularly with the erect growing cultivar, is a promising strategy for maximizing land and water use efficiency under sustainable cropping systems.

In case of soil nutrient status showed in Table 3 & 4, the intercropping systems markedly influenced nutrient

uptake and soil nutrient balance. Treatment T_4 (Sugarcane + Mega Sweet) recorded the highest uptake of N (434.33 kg ha⁻¹), P (119.69 kg ha⁻¹), and K (435.69 kg ha⁻¹), indicating greater nutrient demand due to higher total biomass production and improved resource utilization. In contrast, sole sugarcane (T_1) exhibited the lowest nutrient uptake because of comparatively lower total biomass despite producing the highest cane yield. The efficient nutrient uptake under T_4 resulted in lower residual soil nutrients.

The economic evaluation from the farmers' perspective showed that the sugarcane + sweet sorghum intercropping system recorded the highest gross income (Rs. 5,17,500/ha) and net income (Rs. 4,08,500/ha) compared to sole sugarcane and sole sweet sorghum cultivation. Intercropping provided an additional income of Rs. 40,800/ha over sole sugarcane, demonstrating its economic advantage despite a comparatively higher production cost.

The comparative analysis revealed that (Table 6), the sugarcane + sweet sorghum intercropping system produced the highest ethanol yield (2682 L ha⁻¹), substantially exceeding sole sugarcane (1320 L ha⁻¹) and sole sweet sorghum (1786 L ha⁻¹). The additional syrup obtained from sweet sorghum (3.9 t ha⁻¹) significantly enhanced total ethanol production. Ethanol from sugarcane was derived from C-molasses, whereas sweet sorghum contributed fermentable syrup, providing an additional 1362 L ha⁻¹ of ethanol without requiring an

Table 6: Comparative ethanol generation from different cropping systems (Sweet sorghum: syrup to ethanol and Sugarcane: C-Molasses to ethanol).

Cropping system	Sole Sugarcane	Sole Sweet Sorghum	Sugarcane + Sweet Sorghum
Crop Cycle Duration	12 Months	4 Months	12 Months
Whole Green Biomass (t/ha)	-	47.00	39.00
Cane yield (t/ha)	132.00	-	120.00
C molasses yield from sugarcane (t/ha) (@4% of cane yield)	5.28	-	4.80
Syrup yield from sweet sorghum (t/ha) (@10% of total biomass)	-	4.7	3.9
Ethanol yield (lit./ha) (@ 250 lit./t of C molasses & 380 lit./ton of syrup)	1320.00	1786.00	2682.00
Additional Ethanol generation (lit./ha)	-	-	1362.00

additional cropping season. The complementary use of both feedstocks improved land-use efficiency and overall biofuel productivity. These findings indicate that integrating sweet sorghum with sugarcane can substantially increase ethanol output per hectare, making the intercropping system a more efficient and sustainable option for bioethanol production. (Mathur *et al.*, 2017; Oktem & Oktem, 2024; Rooney *et al.*, 2014).

Conclusions

The additive intercropping of sweet sorghum in sugarcane proved to be technically feasible and economically advantageous under wide row spacing. Although a moderate reduction in sugarcane yield was observed, the integration of sweet sorghum resulted in: increased total biomass and ethanol output per unit area, improved farm profitability and income stability, Efficient utilization of inter-row space during early crop growth and additional scope for bioenergy diversification (ethanol + CBG)

Among the tested varieties, Mega Sweet emerged as the most promising intercrop due to its higher biomass production and superior ethanol yield potential.

Further, the study highlights that for successful sweet sorghum intercropping, the plant ideotype plays a critical role. Varieties with erect growth habit and optimum canopy architecture are more suitable, as they minimize competition with sugarcane for light, nutrients, and space, thereby ensuring better compatibility and system productivity.

Overall, the findings confirm that such intercropping systems can play a vital role in addressing the dual challenges of increasing biofuel demand and limited land resources, while, enhancing sustainability and resource-use efficiency in sugarcane-based cropping systems.

Acknowledgement

We are thankful to Mr. Sambhaji Kadupatil, Director General, Vasantdada Sugar Institute, Pune for his encouragement during this research work and giving permission to publish this article. Authors are also thankful to scientists and supporting staff of crop production division for their help during the field experimentation.

References

- Almodares, A. and Hadi, M. R. (2009). Production of bioethanol from sweet sorghum: A review. *African Journal of Agricultural Research*, **4**(9), 772–780.
- Lane and Eynon Method (1923). Determination of Reducing Sugars by Means of Fehling's Solution with Methylene Blue as Internal Indicator. *Journal of the Society of Chemical Industry*, **42**, 32T-37T.
- Mathur, S., Umakant A.V., Tonapi V.A., Sharma R. and Sharma M.K. (2017). Sweet Sorghum as Biofuel Feedstock: Recent Advances and Available Resources. *Biotechnology for Biofuels*, **10**, 146. doi: [10.1186/s13068-017-0834-9](https://doi.org/10.1186/s13068-017-0834-9).
- Mathur, S., Umakanth A.V., Tonapi V.A., Sharma R. and Sharma M.K. (2017). *Sweet sorghum as biofuel feedstock: Recent advances and available resources*. *Biotechnology for Biofuels*, **10**, 146.
- Oktem, A. and Oktem A.G. (2024). Bioethanol obtained from soluble sugars in sweet sorghum: Influencing properties and their interrelationships. *Industrial Crops and Products*, **221**, 119351.
- Raseduzzaman, M. and Jensen E.S. (2017). Does intercropping enhance yield stability in arable crop production? A meta-analysis. *European Journal of Agronomy*, **91**, 25–33.
- Rooney, W.L., Blumenthal J., Bean B. and Mullet J.E. (2014). *Sweet sorghum as a bioenergy crop: Literature review*. *Biomass and Bioenergy*, **64**, 348–355.
- Shilpa, V. Chogatapur H.T. Chandranath and Khandagave R.B. (2018). Economics and Intercropping Indices of Sugarcane Based Intercropping System in Plant Cane. *Int. J. Curr. Microbiol. App. Sci.*, **7**(08), 101-107.
- Willey, R.W. and Ruberts E.M. (1979). Mixed cropping. *Advances in Agron.*, **28**, 185-192.