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RESEARCH ARTICLE

Evaluating intercropping systems with sugarcane in Bihars' north-west alluvial plains

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Abstract

Intercropping in sugarcane cultivation is an effective strategy to enhance productivity, optimise resource utilisation and improve farm profitability by incorporating short-duration companion crops within the cropping cycle. This study investigates the performance of diverse sugarcane-based intercropping systems in the North-West Alluvial Plain Zone of Bihar, India, with particular emphasis on key growth parameters, yield attributes and associated economic returns. The experiment was chalked out in randomized block design at the Krishi Vigyan Kendra located in Narkatiyaganj, West Champaran, Bihar. Notably, high-value intercrops such as potato and onion substantially enhanced both gross and net returns, achieving the highest benefit-cost ratios (BCRs). This was primarily due to their synergistic resource utilisation patterns and elevated market demand, which together contributed to superior profitability. Additionally, the inclusion of leguminous intercrops such as lentil and pea resulted in moderate yields. At the same time, these crops enhanced soil fertility through biological nitrogen fixation, making them an environmentally sustainable and economically viable option for smallholder and resource-limited farmers. Results revealed that intercropping significantly influenced growth, yield, system productivity and economic returns. Sugarcane intercropped with potato recorded the highest cane yield (1027 q/ha), land equivalent ratio (1.59), cane equivalent yield (1717 q/ha) and benefit-cost ratio (2.47), followed by lentil and pea intercropping systems. Leguminous intercrops improved yield attributes and system productivity while contributing to soil fertility enhancement. Correlation analysis revealed strong positive associations between germination percentage, plant survival rate, tiller population and cane morphological traits with final yield. These relationships highlight the critical role of vigorous crop establishment in maximising overall productivity. Overall, the study demonstrates that potato and legume-based intercropping systems are agronomically efficient and economically viable options for sustainable sugarcane production in the North-West Alluvial Plain Zone of Bihar.

Keywords: cane equivalent yield; intercrop; land equivalent ratio; millable cane; sugarcane

Introduction

Sugarcane (*Saccharum officinarum* L.) is a major commercial crop cultivated in tropical and subtropical regions, serving as a primary source of sugar, ethanol and bioenergy. In India, it plays a crucial role in rural livelihoods, supporting millions of farmers and sustaining sugar and allied industries. Beyond its economic importance, sugarcane contributes to renewable energy production, carbon sequestration and climate change mitigation through ethanol blending and cogeneration from bagasse. Owing to its long duration and wide row spacing, sugarcane offers substantial scope for intercropping to enhance system productivity and resource-use efficiency (1–3).

India ranks second globally in sugarcane production, with an annual output of approximately 400 million tonnes, cultivated on over 5 million hectares of land in 2024. The crop is central to the Indian economy, sustaining nearly 50 million farmers and an equal number of workers involved in processing and related industries (3). Sugarcane cultivation is concentrated in states like Uttar Pradesh, Maharashtra, Karnataka, Tamil Nadu and Bihar, each contributing significantly to national production. The sugarcane industry in India is a cornerstone of the rural economy, contributing significantly to employment, income generation and national gross domestic product (GDP) (4). The government of India has emphasised ethanol production from sugarcane to reduce dependence on fossil fuels, achieving notable progress in biofuel blending targets. Additionally, sugarcane cultivation serves as a critical source of raw materials for the jaggery and khandsari industries, which are prominent in rural areas. These small-scale enterprises provide livelihood opportunities and cater to domestic markets, emphasising the socio-economic relevance of the crop (5). Despite its importance, sugarcane cultivation in India and worldwide faces several challenges that threaten its sustainability, such as water scarcity, soil degradation and pest infestations, which necessitate adaptive and innovative farming practices.

In the context of sugarcane cultivation, intercropping has gained significant attention due to the unique growth characteristics of sugarcane. As a long-duration crop with wide row spacing and slow initial growth, sugarcane provides an opportunity to grow short-duration intercrops that can utilise available resources efficiently without competing with the main crop (6). In sugarcane cultivation, intercropping is particularly important as it enhances land productivity through short-duration crops, diversifies income and reduces risk, improves resource-use efficiency, promotes soil health and biodiversity and helps break pest and disease cycles, thereby reducing dependence on chemical inputs. The success of intercropping in sugarcane depends on the careful selection of compatible intercrops. Factors such as crop growth habits, resource requirements, market demand and agro-climatic conditions play a crucial role in determining the suitability of intercrops (7). Some common intercrops used in sugarcane systems include wheat, maize, lentil, pea, groundnut, mustard, potato, onion, vegetables, etc.

The North-West Alluvial Plain Zone of Bihar (Latitude: 25° 00′ N to 27°30′ N and Longitude: 83°30′ E to 85°30′ E) is characterised by its fertile alluvial soils, abundant water resources and moderate climatic conditions, making it highly conducive to sugarcane cultivation (8). The region experiences a subtropical climate with distinct wet and dry seasons, providing favourable conditions for both sugarcane and various short-duration crops. However, the region is also prone to challenges such as periodic floods, soil degradation and waterlogging, which necessitate the adoption of resilient and adaptive farming practices. In this agro-climatic context, intercropping offers a viable solution to enhance land use efficiency and stabilise farm incomes. The strategic selection of intercrops can not only improve resource utilisation but also contribute to soil conservation, pest management and overall farm sustainability (9). This study focuses on assessing the suitability of different intercrops with sugarcane in this specific agro-ecological zone to provide insights into optimising cropping systems for better economic and environmental outcomes.

While the benefits of intercropping have been widely recognised, existing research on intercropping with sugarcane in Bihar's North-West Alluvial Plain Zone is limited and fragmented. In the North-West Alluvial Plain Zone of Bihar, sugarcane is predominantly cultivated as a long-duration monocrop under wide row spacing, often resulting in inefficient utilisation of land and resources during the early growth stages. Sugarcane-based intercropping has emerged as a viable agronomic practice in this zone to enhance land-use efficiency, stabilise farm income and reduce the risks associated with monocropping. The favourable alluvial soils and rabi-season climatic conditions of the region support the successful cultivation of short-duration crops such as cereals, legumes, oilseeds and vegetables as intercrops in sugarcane. These systems not only improve overall system productivity and economic returns but also contribute to soil fertility improvement and sustainable intensification of sugarcane-based production systems in the zone.

By addressing the limitations of previous research and adopting a holistic approach, the study seeks to contribute to the development of sustainable and resilient cropping systems that can benefit both farmers and the environment. Therefore, the primary objective of this study is to assess the suitability of various intercrops with sugarcane in the North-West Alluvial Plain Zone of Bihar. The specific objectives are to evaluate various crops for their compatibility with sugarcane based on growth patterns, resource requirements and agronomic performance, to conduct a cost-benefit analysis of intercropping systems to determine their profitability and market feasibility and to develop practical recommendations for farmers and policymakers to optimise intercropping systems in the region. Furthermore, the findings of this study are expected to have broader implications for sugarcane cultivation in similar agro-ecological zones across India and other tropical regions.

Materials and Methods

Details of experimental location and setup

The field experiment on sugarcane based intercropping was conducted during the Autumn season of 2023 at the Krishi Vigyan Kendra located in Narkatiyaganj, West Champaran, Bihar (27° 09'47" N, 84°49'19" E). The site experiences a subtropical climate with a mean temperature ranging from 12–33 °C during the rabi season and receives an annual average rainfall of approximately 1510 mm. The experimental soil was neutral in reaction (pH 7.88), with electrical conductivity of 0.25-dS/m, organic carbon 0.44 %, available N - 214 kg/ha, available P - 24.6 kg/ha and available K - 186 kg/ha. Diethylene Triamine Pentaacetic Acid (DTPA) extractable micronutrients were Zn - 0.57, Cu - 0.83, Fe - 12.4 and Mn - 4.66 mg/kg.

The experiment was laid out in a randomised block design (RBD) comprising 10 treatments and replicated thrice (Table 1). Treatments included traditional sugarcane planting, sugarcane settling transplanting (STT) and 8 sugarcane + intercrop combinations. Each plot measured 24 × 9 m with a 1.5 m buffer between plots. Crop management emphasised maintaining optimal plant population and weed-free conditions. Weed control was achieved through pre-emergence herbicide application followed by manual weeding at 30 days after sowing (DAS). Integrated pest management (IPM) strategies were employed, involving periodic monitoring and targeted interventions. Irrigation was applied according to crop requirements to ensure adequate soil moisture throughout the

Table 1. Details of the package and practices for sugarcane and different intercrops

Treatments	Interventions	Sugarcane							Intercrop						
		Variety	Sowing method	Spacing	Sowing time	Seed rate	Fertilizer dose	Harvesting time	Variety	No. of intercrop rows	Spacing	Sowing time	Seed rate	Fertilizer dose	Harvesting time
T_1	Traditional sugarcane planting	Rajendra ganna – 1	Trench method	90 cm × 45 cm	4th week of October	50 q/ha	N:P:K : 240:60:80 kg/ha	December (Next year)	-	-	-	-	-	-	-
T_2	STT method of sugarcane planting	Rajendra ganna – 1	Trench method	120 cm × 45 cm	4th week of October	20 q/ha	N:P:K : 240:60:80 kg/ha	December (Next year)	-	-	-	-	-	-	-
T_3	Sugarcane + wheat	Rajendra ganna – 1	Trench method	120 cm × 45 cm	4th week of October	20 q/ha	N:P:K : 240:60:80 kg/ha	December (Next year)	DBW - 187	5	20 cm × 10 cm	1st week of November	100 kg/ha	N:P:K : 120:40:40 kg/ha	3rd week of March (Next year)
T_4	Sugarcane + maize	Rajendra ganna – 1	Trench method	120 cm × 45 cm	4th week of October	20 q/ha	N:P:K : 240:60:80 kg/ha	December (Next year)	DMRH - 1308	2	60 cm × 20 cm	1st week of November	20 kg/ha	N:P:K : 120:60:40 kg/ha	2nd week of April (Next year)
T_5	Sugarcane + lentil	Rajendra ganna – 1	Trench method	120 cm × 45 cm	4th week of October	20 q/ha	N:P:K : 240:60:80 kg/ha	December (Next year)	IPL - 220	4	30 cm × 10 cm	1st week of November	45 kg/ha	N:P:K:S : 20:40:40:20 kg/ha	1st week of March (Next year)
T_6	Sugarcane + pea	Rajendra ganna – 1	Trench method	120 cm × 45 cm	4th week of October	20 q/ha	N:P:K : 240:60:80 kg/ha	December (Next year)	Azad Pea - 3	4	30 cm × 10 cm	1st week of November	80 kg/ha	N:P:K:S : 20:40:40:20 kg/ha	1st week of March (Next year)
T_7	Sugarcane + mustard	Rajendra ganna – 1	Trench method	120 cm × 45 cm	4th week of October	20 q/ha	N:P:K : 240:60:80 kg/ha	December (Next year)	Rajendra Sufalam - 1	2	45 cm × 15 cm	1st week of November	5 kg/ha	N:P:K:S : 60:40:40:20 kg/ha	2nd week of March (Next year)
T_8	Sugarcane + linseed	Rajendra ganna – 1	Trench method	120 cm × 45 cm	4th week of October	20 q/ha	N:P:K : 240:60:80 kg/ha	December (Next year)	Sabour Tisi - 2	4	30 cm × 10 cm	1st week of November	25 kg/ha	N:P:K:S : 60:40:40:20 kg/ha	2nd week of March (Next year)
T_9	Sugarcane + potato	Rajendra ganna – 1	Trench method	120 cm × 45 cm	4th week of October	20 q/ha	N:P:K : 240:60:80 kg/ha	December (Next year)	Kufri Sindhuri	2	60 cm × 20 cm	1st week of November	25 q/ha	N:P:K : 120:80:60 kg/ha	1st week of March (Next year)
T_{10}	Sugarcane + onion	Rajendra ganna – 1	Trench method	120 cm × 45 cm	October	20 q/ha	N:P:K : 240:60:80 kg/ha	December (Next year)	Agrifound Dark Red	7	15 cm × 7 cm	1st week of November	10 q/ha	N:P:K : 100:40:40 kg/ha	1st week of March (Next year)

growing season.

Data collection

Comprehensive data on germination percentage were recorded at 30 DAS in traditional sugarcane planting and in STT-planted crops, at 21 DAS in the protray nursery. For the survival percentage, the observation was recorded in the field at 30 DAS for the STT-planted crops and 45 DAS in the case of traditionally planted sugarcane crops. The various growth attributes of the sugarcane crop, such as plant height, number of tillers/plant, number of tillers/ha, leaf width, leaf length, number of leaves/tiller, number of nodes/cane, length of internode and cane girth was recorded after the grand growth stage of the sugarcane crop. For this, randomly 10 sugarcane plants were selected in the standing crop from each replication. However, the yield attributes, i.e., millable cane/ha, individual cane weight and cane yield were documented after harvesting of the crop. The brix percentage, sucrose percentage and purity percentage were recorded from the fresh sugarcane juice using a hand refractometer. For different intercrops after harvesting, only the yield was recorded. For economic analysis cost of cultivation, gross return, net return and benefit cost ratio (BCR) were analysed for sole sugarcane and sugarcane + intercrops.

The land equivalent ratio (LER) was computed using the formula:

$$LER = \left[\frac{Y_{ab}}{Y_{aa}}\right] + \left[\frac{Y_{ba}}{Y_{bb}}\right] \quad \text{(Eqn. 1)}$$

where, Y_{aa} = yield of sugarcane as sole crop; Y_{bb} = yield of wheat, maize, lentil, pea, mustard, linseed, potato and onion as sole crop; Y_{ab} = yield of sugarcane as intercrop and Y_{ba} = yield of wheat, maize, lentil, pea, mustard, linseed, potato and onion as intercrop.

The cane equivalent yield (CEY) was computed using the formula:

$$CEY = \frac{Y_b \times R_b}{R_a} \quad \text{(Eqn. 2)}$$

where, Y_b = yield of wheat, maize, lentil, pea, mustard, linseed, potato and onion as intercrop; R_b = price of the wheat, maize, lentil, pea, mustard, linseed, potato and onion as per minimum support price and R_a = price of sugarcane (₹315/q).

Statistical analysis

Data generated from the field experiment was analysed using Analysis of Variance (ANOVA) in a randomised block design as suggested by earlier research (10). Statistical analyses were conducted using SPSS software version 16.0. To assess significant differences between the mean values, the Duncan multiple range test (DMRT) was employed with a significance threshold of < 0.05. This method enabled the precise identification of which means differed significantly from one another. For visual representation of the data, Microsoft Office Excel 2010 was utilised to generate all figures to illustrate the analytical results.

Results and Discussion

Growth attributes of sugarcane

The study revealed significant variation in germination percentages among sugarcane under different planting treatments (Table 2). The STT method (T_2) recorded the highest germination (89.8 %), far exceeding the traditional planting method (T_1 - 34.9 %). This may be attributed to improved soil aeration, moisture and nutrient availability under the STT system (11). Intercropping with lentil (T_5), onion (T_{10}) and pea (T_6) also resulted in high germination (85–88 %), likely due to reduced competition or facilitative effects, whereas mustard (T_7) showed the lowest (80.7 %), possibly influenced by allelopathic compounds or stronger competition for light and nutrients (12).

Survival percentage varied significantly across treatments (Table 2). T_1 had the lowest survival (65.5 %), while T_9 achieved the highest (92.0 %). Treatments involving T_2, T_5, T_6 and T_{10} maintained high survival rates (88–91 %), with minor differences among them. The superior performance of STT and intercrop systems indicates better soil moisture conservation, pest suppression and resource sharing compared to the conventional system (13, 14).

Significant variation in plant height was observed among treatments (Table 2). Sugarcane intercropped with potato (T_9) recorded the maximum height (278 cm), significantly outperforming other treatments, likely due to better intercrop compatibility and improved nutrient and water availability (15). In contrast, intercropping with mustard (T_7 - 234 cm) and maize (T_4 - 237 cm) resulted in the shortest plants, possibly due to stronger competition for light, water and nutrients (16).

The STT method of planting (T_2) produced the highest number of tillers per plant (5.59), significantly exceeding all other treatments (Table 2). This advantage can be attributed to optimised spacing and efficient resource allocation under the STT system, which favours tiller initiation and development (17). Sugarcane intercropped with potato (T_9) also showed a high tiller count (5.18), suggesting complementary growth dynamics and

Table 2. Effect of different intercrops with sugarcane on growth attributes of sugarcane

Treatments	Germination (%)	Survival (%)	Plant height (cm)	No. of tiller /plant	Leaf width (mm)	Leaf length (cm)	No. of leaf /tillers
T_1	34.9a	65.5a	253bc	4.28ab	19.6b	162	11.0
T_2	89.8c	89.2b	262cd	5.59d	22.5d	164	11.0
T_3	81.7bc	88.6b	244ab	4.39abc	17.6a	159	12.0
T_4	82.9bc	86.6b	237a	4.29ab	16.7a	156	11.7
T_5	88.1bc	90.9b	269de	5.05bcd	21.7cd	162	10.7
T_6	85.5bc	88.5b	267d	4.93abcd	21.4cd	161	10.7
T_7	80.7b	84.2b	234a	4.16a	17.3a	158	10.3
T_8	83.1bc	87.6b	252bc	4.63abc	20.4bc	160	9.33
T_9	84.3bc	92.0b	278e	5.18cd	21.7cd	162	11.0
T_{10}	86.2bc	89.6b	267d	4.67abc	20.6bc	160	11.3
SEm±	2.47	2.57	3.48	0.24	0.45	2.06	0.80
CD ($p \leq 0.05$)	7.33	7.63	10.3	0.72	1.35	NS	NS

Values are expressed as a mean of three replicates and different letters for each parameter column-wise show significant differences at $p \leq 0.05$ by Duncan's multiple range test.

reduced competitive stress.

Tiller population per hectare differed significantly among treatments (Fig. 1). The STT method (T_2) recorded the highest tiller density (93500/ha), markedly higher than traditional planting (T_1, 76000/ha), reflecting improved plant establishment and resource-use efficiency. Similarly, sugarcane intercropped with potato (T_9) achieved a high tiller population (89000/ha). In contrast, mustard (T_7) and maize (T_4) intercrops resulted in lower tiller densities (79200 and 80200/ha, respectively), likely due to increased interspecific competition (18).

The highest number of millable canes was recorded under the STT method (T_2 - 77100/ha), significantly surpassing the traditional planting system (T_1 - 64000/ha) (Fig. 1). Among intercropping treatments, potato (T_9), lentil (T_5) and pea (T_2) produced higher millable cane counts (71800–73600/ha) compared with maize (T_4) and mustard (T_7). The superior performance of legume-based systems may be attributed to improved soil nitrogen availability through biological nitrogen fixation (19).

Leaf width varied significantly across treatments (Table 2). The widest leaves were observed under the STT method (T_2 - 22.5 mm), indicating favourable growth conditions. In contrast, maize (T_4 - 16.7 mm) and wheat (T_3 - 17.6 mm) intercrops resulted in narrower leaves, suggesting possible growth suppression due to competition (20). Intercropping with lentil (T_5) and pea (T_6) maintained leaf widths comparable to the STT system (21.4–21.7 mm), further supporting the positive influence of legumes on sugarcane growth, likely through enhanced soil fertility (21).

The study examined the impact of different planting methods and intercropping strategies on sugarcane leaf length and the number of leaves/tiller (Table 2). Statistical analysis revealed that neither parameter exhibited significant variation ($p \leq 0.05$) across the treatments.

Yield attributes of sugarcane

The effect of different intercropping on the number of nodes/cane and internode length of sugarcane (Table 3) revealed that neither parameter exhibited significant variation ($p \leq 0.05$) across the treatments. The study evaluates the impact of different sugarcane planting systems, including monocropping and intercropping with various companion crops, on cane girth (Table 3). Cane girth was highest in sugarcane intercropped with potato (T_9 - 3.24 cm), followed by sugarcane intercropped with lentil (T_5 - 3.18 cm) and pea (T_6 - 3.15 cm). These results suggest a positive interaction between sugarcane and leguminous crops or tuber crops like potato, potentially due to improved soil fertility and resource optimisation. The STT method of sugarcane planting (T_2) improved cane girth (3.12 cm) in comparison to traditional sugarcane planting (T_1), possibly due to better plant spacing and resource utilisation (22).

Cane weight was highest in sugarcane intercropped with potato (T_9 - 1.08 kg/cane), followed by sugarcane intercropped with lentil (T_5 - 1.06 kg/cane) and pea (T_6 - 1.05 kg/cane) (Fig. 2). These findings suggest that intercropping with leguminous crops or potato can enhance cane growth, potentially due to improved soil fertility and nutrient availability (23). The STT method (T_2) showed a significant improvement in cane weight (1.01 kg/cane) compared to traditional planting. This indicates that modern techniques like STT can positively influence sugarcane growth, likely by optimising planting density and resource utilisation.

The highest cane yield was observed in sugarcane intercropped with potato (T_9 - 1027 q/ha), followed by sugarcane intercropped with lentil (T_5 - 1008 q/ha) and pea (T_6 - 991 q/ha) (Fig. 2). These findings suggest that intercropping with nitrogen fixing legumes or potato enhances sugarcane productivity, likely due to improved nutrient availability and better resource use efficiency. The STT method (T_2) significantly increased the yield (982 q/ha) compared to traditional planting, indicating the benefits of modern planting techniques in optimising sugarcane performance (24). Conversely, the traditional planting method (T_1) recorded the lowest yield (757 q/ha), highlighting the limitations of conventional practices in achieving higher productivity. The study assessed the influence of various sugarcane planting systems, including traditional and intercropping methods, on juice quality parameters such as brix (%), sucrose (%) and purity (%) (Table 3). The statistical analysis revealed no significant differences ($p \leq 0.05$) among treatments for these parameters.

Yield of intercrops

Among the treatments, sugarcane intercropped with potato (T_9) recorded the highest yield (109 q/ha), followed by sugarcane intercropped with onion (T_{10} - 84.3 q/ha) (Table 3). These findings suggest that potato and onion are particularly well-suited to intercropping with sugarcane, likely due to their complementary resource utilisation and reduced competition with sugarcane (25). In contrast, leguminous crops such as lentil (T_5 - 9.69 q/ha) and pea (T_6 - 8.25 q/ha) exhibited comparatively lower yields. This may reflect slower biomass accumulation or specific growth dynamics that prioritise soil nitrogen enrichment over yield. Intercropping with mustard (T_7 - 11.2 q/ha) and linseed (T_8 - 6.72 q/ha) also

Table 3. Effect of different intercrops with sugarcane on the yield attributes of sugarcane

Treatments	Number of nodes /cane	Length of internode (cm)	Cane girth (cm)	Brix (%)	Sucrose (%)	Purity (%)	Intercrop yield (q/ha)
T_1	20.0	12.2	2.75a	16.3	13.3	82.0	-
T_2	22.1	13.6	3.12cde	16.2	13.5	82.3	-
T_3	19.0	12.8	2.89abc	16.2	13.1	79.3	24.6b
T_4	19.1	12.5	2.86ab	16.0	13.4	80.9	48.7c
T_5	21.0	12.9	3.18de	16.2	13.4	80.7	9.69a
T_6	21.1	12.7	3.15de	16.1	13.3	81.3	8.25a
T_7	19.3	12.2	2.81ab	16.2	13.2	79.2	11.2a
T_8	19.9	12.6	2.95abcd	16.3	13.3	80.0	6.72a
T_9	22.3	13.1	3.24e	16.3	13.5	81.4	109e
T_{10}	20.7	13.0	3.03bcde	16.0	13.1	78.7	84.3d
SEm±	1.14	0.35	0.08	0.14	0.17	1.32	1.59
CD ($p \leq 0.05$)	NS	NS	0.23	NS	NS	NS	4.82

Values are expressed as a mean of three replicates and different letters for each parameter column-wise show significant differences at $p \leq 0.05$ by Duncan's multiple range test.

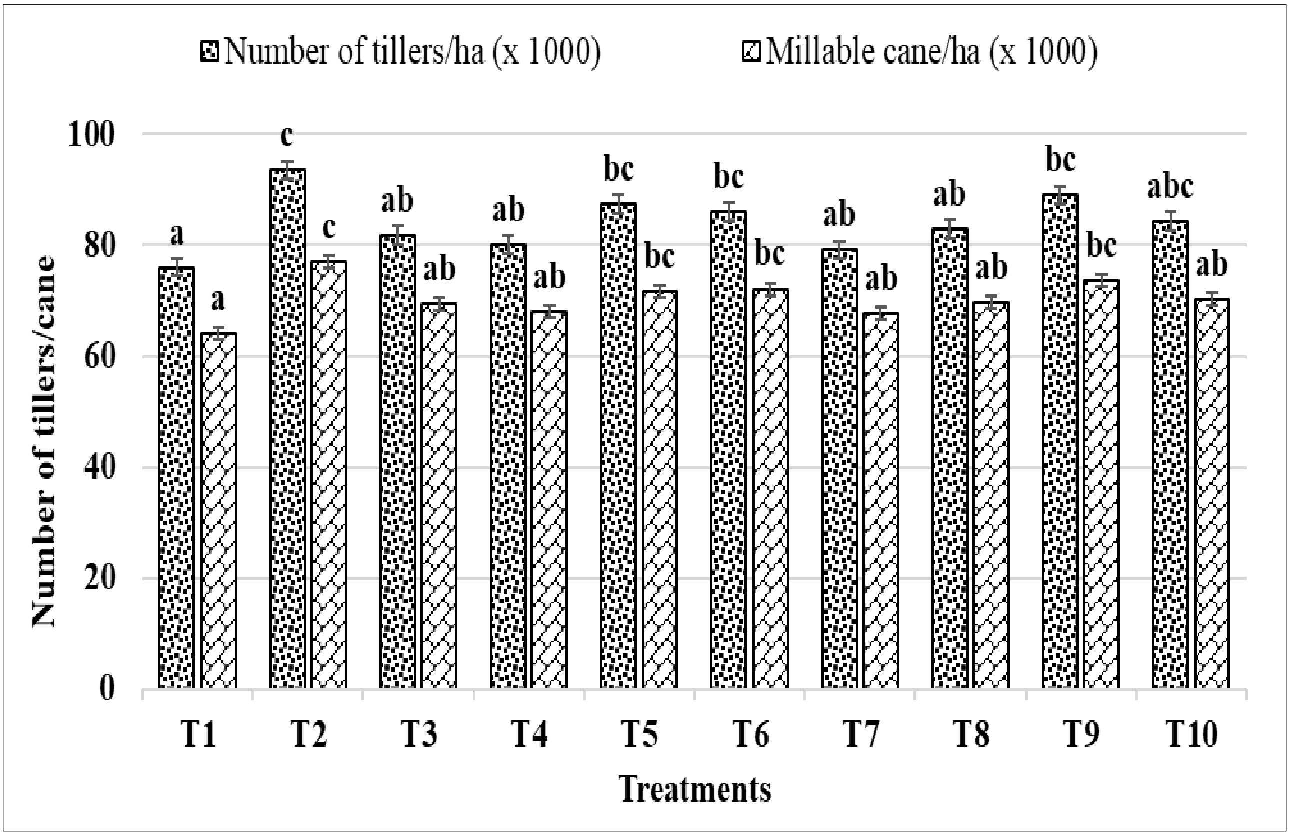

Fig. 1. Effect of different intercrops with sugarcane on the number of tillers and millable cane per hectare of sugarcane. Values are expressed as a mean of three replicates and different letters for each parameter show significant differences at $p \leq 0.05$ by Duncan's multiple range test.

Error bars identify the standard error of different treatments.

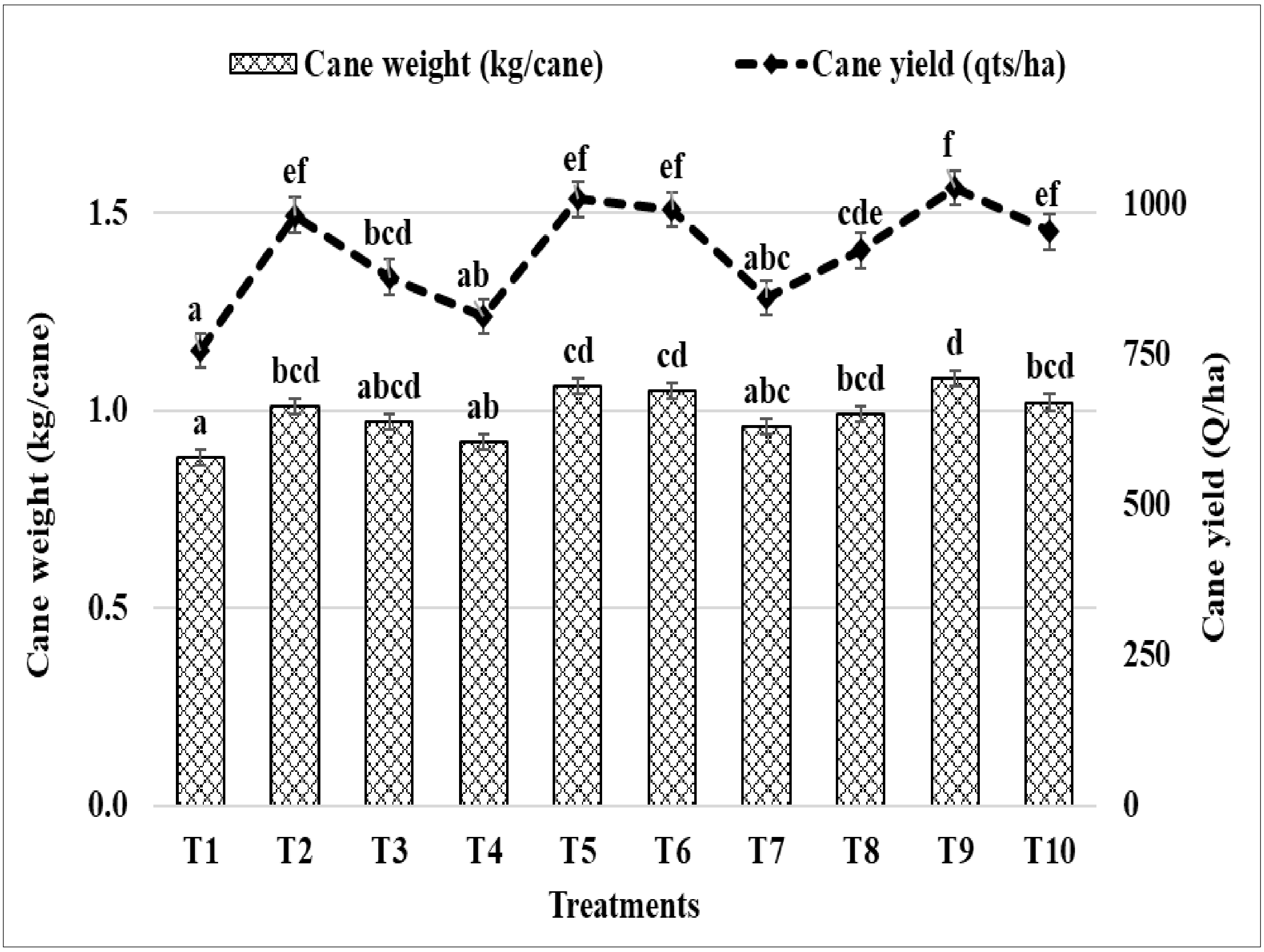

Fig. 2. Effect of different intercrops with sugarcane on cane weight and cane yield of sugarcane. Values are expressed as a mean of three replicates and different letters for each parameter show significant differences at $p \leq 0.05$ by Duncan's multiple range test.

Error bars identify the standard error of different treatments.

showed modest yield, possibly due to competition for light or nutrients.

Economics of sugarcane-based intercropping

Among the treatments, the STT method of sugarcane planting (T_2) demonstrated the lowest cultivation costs (₹150075) (Table 4), comparable to other cost-effective intercropping treatments such as sugarcane + mustard (T_7 - ₹150043/ha) and sugarcane + linseed (T_8 - ₹147729/ha). In contrast, intercropping sugarcane with potato (T_9 - ₹219560) and onion (T_{10} - ₹222956) resulted in the highest cost of cultivation, significantly exceeding all other treatments. Intermediate cost of cultivation was observed in combinations such as sugarcane + lentil (T_5 - ₹160290/ha) and sugarcane + pea (T_6 - ₹156519/ha), respectively. These findings suggest that legumes can serve as economically moderate intercropping options, balancing input costs with potential agronomic benefits (26).

The sugarcane + potato (T_9) recorded the highest gross return (₹542821/ha) and net return (₹323261/ha), significantly outpacing other treatments (Table 4). Similarly, sugarcane + onion (T_{10}) exhibited substantial economic benefits, with respective gross and net returns of ₹512132/ha and ₹289176/ha. These results underscore the profitability of these intensive intercropping systems, potentially linked to the high market value of these crops. Intermediate returns were observed in sugarcane + lentil (T_5), sugarcane + pea (T_6) and sugarcane + linseed (T_8), with net returns ranging between ₹183860/ha and ₹213679/ha. Although the STT method of sugarcane planting (T_2) also demonstrated improved gross (₹309414/ha) and net returns (₹159338/ha), surpassing traditional planting (T_1) and highlighting its cost-effectiveness. The data suggest that intercropping sugarcane with high-value crops such as potato and onion maximises economic output, albeit with potentially higher resource requirements (27). Conversely, intercropping with legumes like lentil and pea offers a balance between profitability and sustainability.

The BCR analysis for different sugarcane planting methods and intercropping systems highlights notable differences in economic efficiency (Table 4). The sugarcane intercropped with potato (T_9) exhibited the highest BCR (2.47), followed by intercropping with lentil (T_5 - 2.34) and onion (T10 - 2.30). Intermediate BCR values were observed in sugarcane + linseed (T_8 - 2.25), sugarcane + pea (T_6 - 2.17) and sugarcane + mustard (T_7 - 2.18). High-value intercropping combinations, particularly with potato and onion, are recommended for maximising economic returns (28). For resource limited scenario, legumes and mustard offer a sustainable option with competitive returns.

System productivity of sugarcane-based intercropping

Intercropping significantly enhanced the LER, with sugarcane + potato (T_9) showing the highest value of 1.59, indicating a 59 % increase in land productivity over the sole sugarcane crop (Table 4). Similarly, sugarcane + lentil (T_5 - 1.56) and sugarcane + pea (T_6 - 1.52) also achieved high LER, reflecting their potential to maximise productivity through complementary crop interactions. Intermediate LER values were observed in sugarcane intercropped with maize (T_4 - 1.41), mustard (T_7 - 1.41) and linseed (T_8 - 1.48). Intercropping with high-value crops such as potato and onion significantly improves land use efficiency, aligning with sustainable agricultural practices. Meanwhile, legumes such as lentil and pea provide a favourable balance between productivity and resource use, making them attractive options for smallholder farmers aiming for sustainable intensification (29).

Among intercropping systems, sugarcane intercropped with potato (T_9) recorded the highest CEY of 1717 q/ha, statistically outperforming all other treatments (Table 4). Sugarcane + onion (T_{10}) also demonstrated high productivity, achieving a CEY of 1623 q/ha. These results underscore the potential of intercropping sugarcane with high-value crops to optimise yield. High CEYs observed in potato and onion intercropping systems suggest these crops are particularly beneficial for maximising economic returns (30). Conversely, legumes such as lentils provide a balance between moderate yield improvement and potential soil health benefits.

The percentage increase in cane yield over traditional planting (T_1) was most notable for sugarcane intercropped with potato (T_9), achieving a 36.4 % increase, followed by sugarcane with lentil (T_5 - 33.8 %) and sugarcane with pea (T_6 - 31.3 %) (Fig. 3). These treatments demonstrated statistically significant improvements, reflecting the suitability of these intercrops in enhancing resource utilization and productivity. Conversely, intercropping with maize (T_4) resulted in the lowest yield increment (7.74 %), indicating limited compatibility or competition for resources in this combination. Compared to the STT planting method, sugarcane intercropped with potato (T_9) also recorded the highest yield increase (5.02 %), followed by sugarcane with lentil (T_5 - 3.05 %) and pea (T_6 - 1.17 %). While sugarcane combinations with maize (T_4 : -17.0 %), mustard (T_7 : -13.7 %) and wheat (T_3: -10.2 %) showed reductions in yield. These declines may

Table 4. Effect of different intercrops with sugarcane on economics and system productivity

Treatments	Cost of cultivation (₹/ha)	Gross return (₹/ha)	Net return (₹/ha)	Benefit-cost ratio	Land equivalent ratio	Cane equivalent yield (q/ha)
T_1	167210d	235196a	67986a	1.41a	1.00a	-
T_2	150075a	309414b	159338b	2.06b	1.00a	-
T_3	151076ab	328751c	177674c	2.18c	1.34b	1046a
T_4	167210d	359661e	192451d	2.15bc	1.41bc	1137ab
T_5	160290c	373969f	213679e	2.34d	1.56cd	1193b
T_6	156519bc	340379d	183860cd	2.17c	1.52cd	1082a
T_7	150043a	326605c	176562c	2.18c	1.41bc	1038a
T_8	147729a	331687cd	183957cd	2.25cd	1.48bcd	1051a
T_9	219560e	542821h	323261g	2.47e	1.59d	1717c
T_{10}	222956e	512132g	289176f	2.30d	1.51cd	1623c
SEm±	1899	3570	4391	0.04	0.05	34.0
CD ($p \leq 0.05$)	5641	10605	13044	0.10	0.15	103

Values are expressed as a mean of three replicates and different letters for each parameter column-wise show significant differences at $p \leq 0.05$ by Duncan's multiple range test.

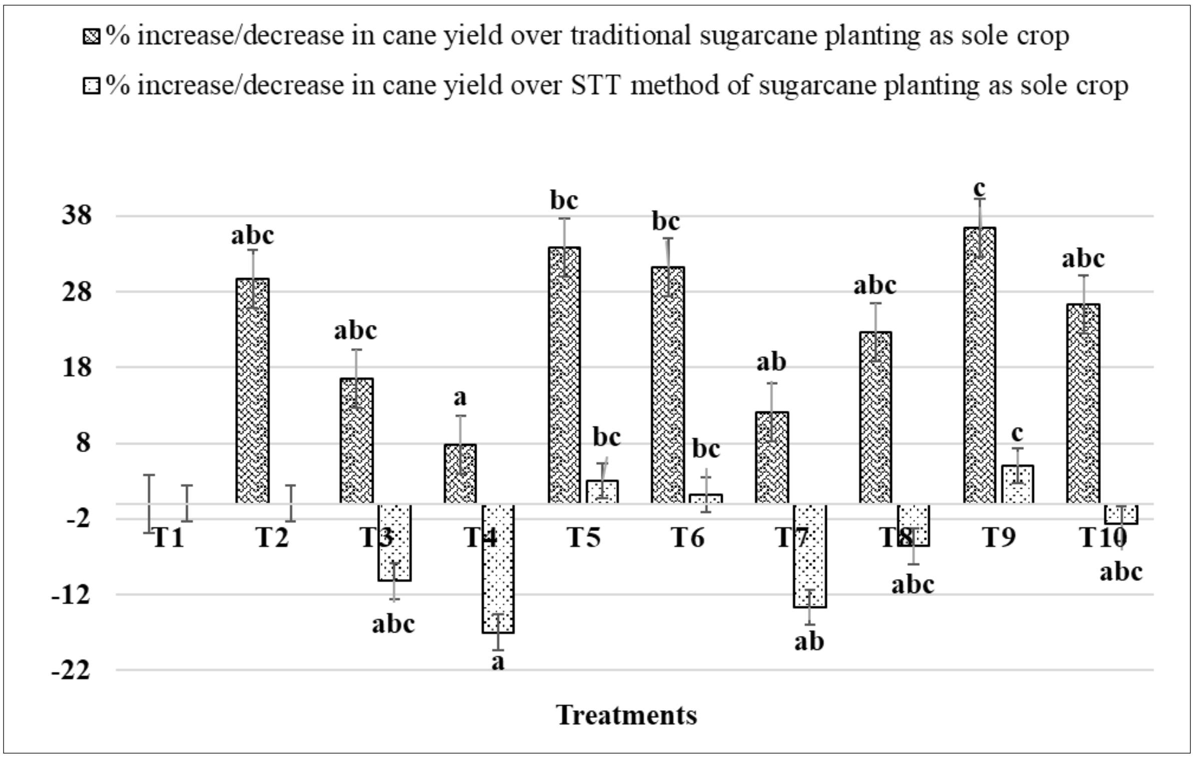

Fig. 3. Effect of different intercrops with sugarcane on percentage increase/decrease in cane yield over traditional sugarcane planting as sole crop and STT method of sugarcane planting as sole crop. Values are expressed as a mean of three replicates and different letters for each parameter show significant differences at $p \leq 0.05$ by Duncan's multiple range test. Error bars identify the standard error of different treatments.

result from interspecies competition or differences in resource requirements and growth cycles. Intercropping with legumes appears to be beneficial, likely due to their nitrogen-fixing ability, which enhances soil fertility and complements the nutrient needs of sugarcane (31). Potato, with its short growing period and minimal competition for above-ground resources, aligns well with sugarcane growth. However, cereals like maize and mustard might compete intensively for nutrients, water and light, thereby negatively affecting sugarcane yields (16).

The observation showed that intercropping sugarcane with potato (T_9) achieved the highest percentage increase in CEY (128 %), followed by sugarcane with onion (T_{10} - 115 %) (Fig. 4). These substantial gains underscore the compatibility of these intercrops with sugarcane in optimising land productivity. Sugarcane intercropped with lentil (T_5) also showed a notable improvement in CEY (58.1 %). On the other hand, sugarcane intercropped with mustard (T_7 - 37.9 %) and wheat (T_3 - 38.6 %) demonstrated relatively moderate gains, highlighting the need for optimised management practices to achieve higher efficiencies in these combinations. In comparison to the STT method, potato (T_9) and onion (T_{10}) again showed the highest increases in CEY, recording an increment of 75.6 % and 65.6 %, respectively. These results reinforce their effectiveness in sugarcane-based intercropping systems. Sugarcane intercropped with lentil (T5) contributed 21.8 % increase and maize (T_4) showed a 15.9 % increase. Other intercrops, such as wheat (T_3 - 6.75 %) and mustard (T_7 - 6.24 %), displayed modest improvements, which might be attributed to competitive interactions or resource-sharing limitations. The pronounced performance of potato and onion as intercrops can be attributed to their complementary growth dynamics, minimal above-ground competition and efficient utilisation of soil resources. These crops have shorter growth cycles and harvest times that align well with the growth requirements of sugarcane, allowing for optimal resource partitioning (14). In contrast, moderate performers such as wheat and mustard might experience more competition for nutrients and water, impacting overall yields. Leguminous intercrops, such as lentil (T_5), contributed to enhanced productivity likely due to their nitrogen-fixing ability, which improves soil fertility and supports the nutrient demands of sugarcane (32).

Correlation

Pearson's correlation matrix was employed to evaluate the relationships among various growth and yield attributes of sugarcane under different intercropping systems (Table 5). A strong positive correlation was observed between germination and survival (r = 0.82***), suggesting that improved germination rates directly enhance plant establishment (33). Plant height exhibited a robust correlation with cane yield (r = 0.72***), reflecting its significance as a determinant of photosynthetic capacity and biomass accumulation. The number of tillers per plant (r = 0.66***) and per hectare (r = 0.56**) also displayed strong positive associations with cane yield, emphasising the importance of tiller development in sugarcane production systems. Leaf width was significantly associated with plant height (r = 0.79***) and cane yield (r = 0.64***), indicating its role in supporting photosynthetic efficiency (34). Cane girth (r = 0.64***) and cane weight (r = 0.70***) exhibited strong positive correlations with cane yield, signifying their direct impact on productivity. However, intercropping practices should focus on enhancing resource allocation to critical growth parameters, such as germination and tillering, which are foundational for establishing high-yielding stands (27).

A Pearson's correlation analysis was conducted to explore the relationships between physiological attributes of sugarcane and economic parameters under intercropping systems (Table 6). Plant height showed moderate yet significant correlations with

Table 5. Pearson's correlation matrix among growth and yield attributes of sugarcane crop under different intercropping

Plant parameters	Germination	Survival	Plant height	No. of tiller/ plant	No. of tiller ('000/ha)	Millable cane ('000/ha)	Leaf length	Leaf width	No. of leaf/ tillers	Number of nodes/cane	Length of internode	Cane girth	Cane weight	Cane yield
Germination	1.00													
Survival	0.82***	1.00												
Plant height	0.18	0.27	1.00											
No. of tiller/plant	0.38*	0.28	0.56**	1.00										
No. of tiller ('000/ha)	0.51**	0.54**	0.46*	0.43*	1.00									
Millable cane ('000/ha)	0.55**	0.47**	0.41*	0.60***	0.43**	1.00								
Leaf length	-0.04	0.01	0.43*	0.46*	0.22	0.35	1.00							
Leaf width	0.20	0.21	0.79***	0.66***	0.61***	0.53**	0.58**	1.00						
No. of leaf/tillers	0.01	-0.10	-0.08	0.02	-0.13	0.09	-0.03	-0.02	1.00					
Number of nodes/cane	0.14	0.16	0.48**	0.58***	0.48**	0.33	0.17	0.41*	-0.29	1.00				
Length of internode	0.38*	0.34	0.47**	0.36	0.32	0.55**	0.34	0.36	0.05	0.25	1.00			
Cane girth	0.53**	0.55**	0.63***	0.53**	0.70***	0.56**	0.27	0.63***	0.08	0.38	0.31	1.00		
Cane weight	0.53**	0.50**	0.54**	0.62***	0.30	0.51**	0.36	0.55**	-0.11	0.42*	0.33	0.52**	1.00	
Cane yield	0.62***	0.60***	0.72***	0.66***	0.56**	0.54**	0.29	0.64***	-0.17	0.40*	0.46*	0.64***	0.70***	1.00

*Significance at $p < 0.05$ level, **significance at $p < 0.01$ level and ***significance at $p < 0.001$ level.

Table 6. Pearson's correlation matrix among physiological attributes of sugarcane crop and economics under different intercropping

Parameters	Cost of cultivation	Gross return	Net return	BCR
Germination	0.05	0.49**	0.63***	0.86***
Survival	0.18	0.55**	0.66***	0.81***
Plant height	0.54**	0.55**	0.51**	0.30
No. of tiller/plant	0.12	0.25	0.28	0.28
No. of tiller ('000/ha)	0.12	0.32	0.37*	0.43**
Millable cane ('000/ha)	0.05	0.30	0.37*	0.47**
Leaf length	0.11	0.03	0.01	-0.10
Leaf width	0.23	0.27	0.26	0.18
No. of leaf/tillers	0.16	0.09	0.05	-0.05
Number of nodes/cane	0.21	0.26	0.26	0.19
Length of internode	0.19	0.26	0.27	0.23
Cane girth	0.29	0.49**	0.53**	0.52**
Cane weight	0.25	0.49**	0.55**	0.58***
Cane yield	0.27	0.53**	0.60***	0.63***

*Significance at $p < 0.05$ level, **significance at $p < 0.01$ level and ***significance at $p < 0.001$ level.

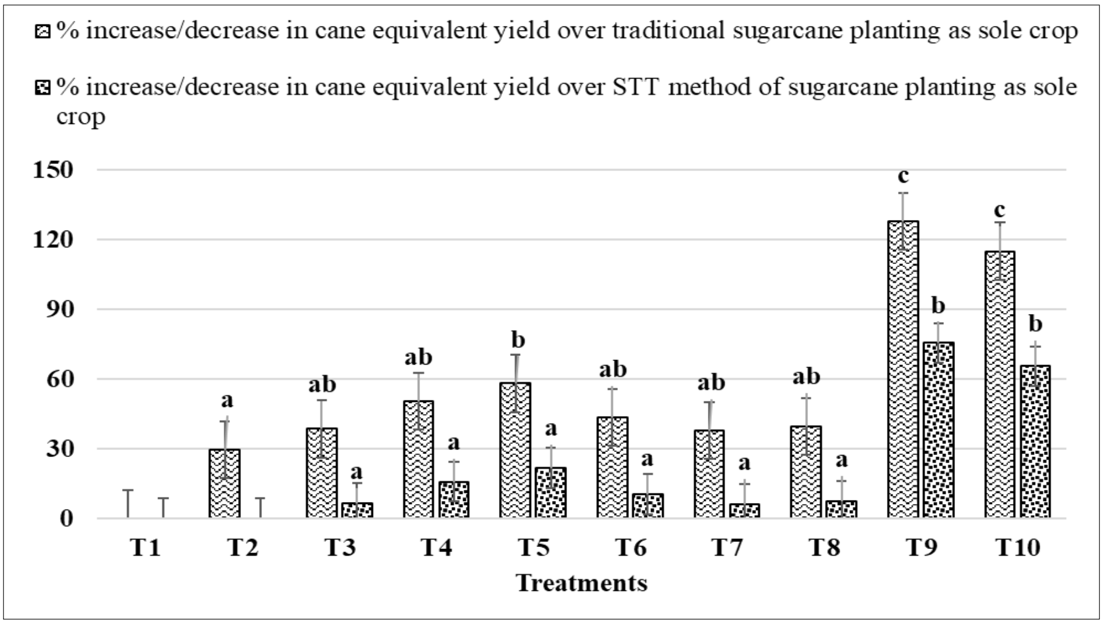

Fig. 4. Effect of different intercrops with sugarcane on percentage increase/decrease in cane equivalent yield over traditional sugarcane planting as sole crop and STT method of sugarcane planting as sole crop. Values are expressed as a mean of three replicates and different letters for each parameter show significant differences at $p \leq 0.05$ by Duncan's multiple range test. Error bars identify the standard error of different treatments.

cost of cultivation (r = 0.54**), gross return (r = 0.55**) and net return (r = 0.51**). This highlights the dual impact of taller plants on increased inputs and potential returns, underscoring the importance of optimising height for resource efficiency (35). However, their positive correlations with BCR (r = 0.43** and r = 0.47**, respectively) indicate that their financial impact might depend on the balance between input costs and output value. Cane girth and cane weight emerged as strong predictors of economic returns, with significant correlations observed for gross return (r = 0.49**), net return (r = 0.53**) and BCR (r = 0.52**) for girth, (r = 0.55**) for cane weight and (r = 0.58***) for cane yield. These findings reinforce the importance of robust cane development in driving economic success (36). Cane yield demonstrated a significant positive association with gross return (r = 0.53**), net return (r = 0.60***) and BCR (r = 0.63***). This highlights its central role as a determinant of economic viability in sugarcane intercropping systems.

Conclusion

Sugarcane-based intercropping significantly improved cane yield, land-use efficiency and economic returns compared to sole sugarcane, with potato and legume (lentil and pea) intercrops emerging as the most productive and profitable systems in the North-West Alluvial Plain Zone of Bihar. Strong positive associations between germination, tiller density, cane girth, cane weight and yield underscore the importance of robust crop establishment in system productivity. Future research should focus on evaluating short-duration pulses, vegetables and spice crops, multi-location validation across agro-climatic zones and assessing long-term impacts of intercropping on soil health, water-use efficiency and carbon dynamics to further strengthen sustainable sugarcane production systems.

Authors' contributions

AP contributed to conceptualization and experimental design; carried out field research work, data collection and maintenance of experimental plots; and assisted in writing the original draft. RPS contributed to conceptualization and experimental design; critically revised and edited the manuscript. GK contributed to conceptualization and experimental design; carried out field research work, data collection and maintenance of experimental plots; and assisted in writing the original draft. PM contributed to conceptualization and experimental design; carried out field research work, data collection and maintenance of experimental plots; and assisted in writing the original draft. APD contributed to conceptualization and experimental design; performed software-related work and data visualization; and assisted in revising and editing the manuscript. BKS carried out field research work, data collection and maintenance of experimental plots; and assisted in revising and editing the manuscript. RMR carried out field research work, data collection and maintenance of experimental plots. AK[1] carried out field research work, data collection and maintenance of experimental plots; and assisted in revising and editing the manuscript. AK[2] performed software-related work and data visualization. KKM performed software-related work and data visualization. D performed software-related work and data visualization. SKR performed software-related work and data visualization; assisted in formal data analysis and interpretation. MS performed formal data analysis, interpreted the results and assisted in revising and editing the manuscript. VKD performed formal data analysis and interpretation; and assisted in writing the original draft. MKM performed formal data analysis and interpretation; and assisted in writing the original draft. All authors have read and agreed to the published version of the manuscript. [AK[1] stands for Ashutosh Kumar and AK[2] stands for Arun Kumar].

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

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