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CONTENTS

Impact of Integrated Nutrient Management (INM) on growth, yield, quality and soil fertility status in sugarcane-ratoon system

JYOTI PAWAR* and DHEER SINGH

Department of Agronomy, College of Agriculture, G.B. Pant University of Agriculture and Technology, Pantnagar -263145 (U.S. Nagar, Uttarakhand)
**Corresponding author's email id: purva3108@gmail.com*

ABSTRACT: A trial was conducted at Norman E. Borlaug Crop Research Centre, G.B. Pant University of Agriculture and Technology, Pantnagar (Uttarakhand) to study the impact of integrated nutrient management on growth, yield, quality and soil fertility status in sugarcane-ratoon system, Integrated nutrient management practices involving combinations of inorganics (NPK) + organic sources (FYM, biofertilizers, trash incorporation) were tested along with inorganic fertilizer alone. The experiment was laid out in randomized block design with ten treatments in three replications. Significantly higher cane yield (78.8 and 74.5 t ha^{-1}) was recorded in T_6-FYM/Compost @ 20 t ha^{-1} +soil test based recommendation over rest of the treatments except T_5-FYM/Compost @ 20 t ha^{-1} + 100% RDF and T_{10}- RDF+ S+ Zn in both plant and ratoon crops, respectively. The cane yield in T_6 was increased by 15.4% in planted cane and 13.7 % in ratoon crop against the treatment in which NPK was applied alone in both the crops. Similarly, CCS yield and sucrose % was also statistically at par in these treatments. Organic carbon %, available N, P and K was significantly higher in T_6 and T_5 over rest of the treatments in plant and ratoon crops.

Key words: Biofertilizer, Cane yield, INM, nutrient, sugarcane.

Sugarcane (*Saccharum officinarum* L.) is a major cash crop supporting sugar industry next to textile in India. It plays a vital role in the Indian economy by contributing approximately 2.0% to national GDP. Burgeoning population coupled with plateauing yields, declining factor productivity and escalating cost of production of sugarcane in recent years have posted alarming concerns for the researchers as well as policy makers. Sugarcane, being an exhaustive crop, requires more chemical fertilizers application for getting higher cane yield. In India the doses recommended range from 70–400 kg N, 10–80 kg P_2O_5 and 20–141 kg K_2O ha^{-1} (Singh and Yadav, 1996). Continuous use of inorganic fertilizers and plant protection chemicals potentially impair the soil microbial activity, leading to poor soil health (Singh *et al.,* 2007). Imbalanced application of fertilizers resulted in poor yields, deterioration in soil fertility and emergence of multiple nutrient deficiencies. Situation therefore warrants for integrated use of organic sources with chemical fertilizer, which conserves the nutrients, releases nutrients at slow rate and improves the physical, chemical and biological condition of the soil. At present, sustainability of the crop and soil productivity is a burning issue, the integrated use of organics and inorganics needs to be emphasized to use nutrients and energy more efficiently than conventionally managed system (Mader *et al.,* 2002). INM approach improves and sustains soil fertility and provides a sound basis for crop production systems to meet the changing needs through optimization of the benefits from all possible sources of plant nutrients in an integrated manner (FAO, 2001). The Integrated Nutrient Management (INM) approach—entailing combined application of organic manures, chemical fertilizers, and biofertilizers—has gained prominence for enhancing productivity while maintaining soil health. Recent studies have further validated the positive effects of INM practices on yield and soil nutrient balance (Kumar *et al*., 2018; Gupta *et al*., 2020; Rathore *et al*., 2022). Kaur and Singh (2021) emphasized the role of INM in optimizing microbial activity and sustaining long-term productivity. Similarly, Satyanarayana *et al.* (2023) demonstrated that FYM combined with biofertilizers and recommended NPK doses significantly enhanced cane and sugar yield in subtropical conditions. Furthermore, a multi-location study by ICAR (2020) on sugarcane under

INM revealed improved carbon sequestration and resource use efficiency.

Keeping the above facts in view, an experiment entitled "Impact of integrated nutrient management on growth, yield, quality and soil fertility status in sugarcane-ratoon system" was carried out during 2015-16 (plant crop) and 2016-17 (ratoon crop) addressing the current demand for sustainable yet high-yielding crop practices.

Despite previous studies demonstrating the benefits of integrated nutrient management (INM) in sugarcane, there remains limited information on the effectiveness of combining soil-test based inorganic fertilization with organic manures and biofertilizers specifically in sugarcane-ratoon systems under subtropical conditions. This study hypothesizes that the integration of organic manures and biofertilizers with soil test-based fertilizer recommendations would significantly enhance sugarcane growth, yield, juice quality, and sustain soil fertility better than conventional inorganic fertilizer use alone.

MATERIALS AND METHODS

A field experiment was conducted at Norman E. Borlaug Crop Research Centre, G.B. Pant University of Agriculture and Technology, Pantnagar (Uttarakhand). Experiment was laid out in Randomized Block Design with 10 treatments in 3 replications. Three budded setts of sugarcane variety 'Co Pant 5224' were planted by flat bed method in furrows at 75 cm apart on 19th February, 2015 and ratoon crop was initiated on 22nd February, 2016, after harvesting of planted cane. Planted cane and ratoon crop was raised as per recommended package and practices and nutrient management was done as per (Table 1) in both the crops. The soil of the experimental field was silty clay loam in texture, high in organic carbon (1.01%), low in available nitrogen (230.2 kg ha^{-1}), medium in available phosphorous (43.6 kg P_20_5 ha^{-1}) and potassium content (236.3 kg K_2O ha^{-1}). Recommended dose of fertilizers applied for planted cane and ratoon were 150: 75: 50 and 180: 75: 50 kg NPK ha^{-1}, respectively. Soil test based recommendation is 188: 94: 62 kg NPK ha^{-1} in plant crop and 225: 94: 62 kg NPK ha^{-1} in ratoon crop. Half of the nitrogen along with full phosphorous and potassium was applied as basal. Remaining N was top dressed within 90 days after planting (before onset of monsoon) up to end of June in both the crops. Biofertilizers (Azotobacter + PSB) @ 12.5 kg ha-1 were applied. Trash material of planted cane @ 10 t ha^{-1} was thoroughly applied over the ratoon field as per treatments, which was decomposed with Trichoderma culture @ 0.5 kg t^{-1} of trash. Observations on shoot population and dry matter accumulation were computed at 150 days after planting in plant and ratoon cane. Soil samples were analyzed for organic carbon, available N, P and K by standard methods. The experimental plots measured 6 m × 6 m (gross plot size 36 m²). The field trial followed a Randomized Block Design (RBD) with three replications per treatment. Standard agronomic practices, including uniform irrigation, weed management, and pest control, were employed. Statistical analysis was carried out using analysis of variance (ANOVA) technique to determine the significance of treatment effects at the 5% probability level ($p<0.05$).

RESULTS AND DISCUSSION

The positive responses observed in growth parameters under INM treatments can be attributed to the combined benefits of nutrient supply, enhanced microbial activity, and improved soil structure. Organic manures provide slow-release nutrients and stimulate microbial biomass, which in turn enhances nutrient mineralization and availability to the plants. These synergistic effects have been corroborated by several studies (Kaur and Singh, 2021; Gupta *et al.*, 2020).

Shoot population

Shoot population (216 and 165.3 thousand ha^{-1}) was recorded significantly higher in the treatment T_6-FYM/Compost @20 t ha^{-1} + soil test based recommendation in plant and ratoon crop, respectively as compared to rest of the treatments, being at par with application of FYM/Compost @ 20 t ha^{-1} + 100% RDF (T_5) and RDF+Zn+S (T_{10}) (Table 2). The lowest shoot population (154.3 and 137.0 thousand ha^{-1}) was recorded in T_1-50% RDF

Table 1: Treatment details

Treatments	Sugarcane (plant crop)	Ratoon
T1	50% RDF*	50% RDF + trash @ 10 t ha^{-1}
T2	100% RDF	100% RDF+ trash @ 10 t ha^{-1}
T3	Soil test based recommendation**	Application of trash at 10 t ha^{-1}+ soil test basis (NPK application)
T4	Application of FYM/ Compost @ 20 t ha^{-1} + 50% RDF (inorganic source)	Application of FYM/ Compost @ 20 tonnes/ha + 50% RDF (inorganic source)
T5	Application of FYM/Compost @ 20 t ha^{-1} + 100% RDF (inorganic source)	Application of FYM/ Compost @ 20 t ha^{-1}+ 100% RDF (inorganic source)
T6	Application of FYM/Compost @ 20 t ha^{-1} + inorganic nutrient application based on soil test (rating chart)	Application of FYM/Compost @ 20 t ha^{-1} + inorganic nutrient application based on soil test (NPK application)
T7	Application of FYM/Compost @10 t ha^{-1} + Biofertilizer (*Azotobacter*/ *Acetobacter* + PSB) + 50% RDF	Application of FYM/Compost @ 10 t ha^{-1} + Biofertilizer (*Azotobacter*/ *Acetobacter* + PSB) + 50% RDF
T8	Application of FYM/Compost @ 10 t ha^{-1} + Biofertilizer (*Azotobacter/ Acetobacter* + PSB) + 100% RDF	Application of FYM/Compost @ 10 t ha^{-1} + Biofertilizer (*Azotobacter/ Acetobacter* + PSB) + 100% RDF
T9	Application of FYM/Compost @ 10 t ha^{-1} + Biofertilizer (*Azotobacter/ Acetobacter* + PSB) + soil test basis(NPK application)	Application of FYM/Compost @ 10 t ha^{-1} + Biofertilizer (*Azotobacter/ Acetobacter* + PSB) + soil test basis (NPK application)
T10	RDF +S + Zn150 kg N + 75 kg P_2O_5 + 50 kg K_2O + 40 kg S + 25 kg $ZnSO_4$	RDF + S + Zn180 kg N + 75 kg P_2O_5 + 50 kg K_2O + 40 kg S + 25 kg $ZnSO_4$

*Recommended dose of fertilizer (RDF) is 150 kg N + 75 kg P_2O_5 + 50 kg K_2O ha^{-1} in plant crop and 180 kg N + 75 kg P_2O_5 + 50 kg K_2O ha^{-1} in ratoon crop.

**Soil test based recommendation is 188 kg N + 94 kg P_2O_5 + 62 kg K_2O ha^{-1} in plant crop and 225 kg N + 94 kg P_2O_5 + 62 kg K_2O ha^{-1} in ratoon crop.

Table 2: Effect of integrated nutrient management on growth, yield and juice quality of sugarcane plant and ratoon crop

Treatments	Shoot population (000 ha^{-1})		Dry matter accumulation (g/shoot)		Number of millable canes (000 ha^{-1})		Individual cane weight (g)		Cane yield (t ha^{-1})		Sucrose %		CCS yield (t ha^{-1})	
	Plant	Ratoon	Plant	Ratoon	Plant	Ratoon	Plant	Ratoon	Plant	Ratoon	Plant	Ratoon	Plant	Ratoon
T1	154.3	137.0	119.0	107.3	74.7	63.8	806.7	748.6	66.8	62.9	14.7	14.1	5.9	5.5
T2	157.7	140.7	123.8	113.0	74.7	64.4	833.3	784.2	68.3	65.5	14.8	14.3	6.1	5.8
T3	162.7	143.3	125.5	115.7	75.3	66.6	836.7	786.3	70.9	67.6	15.6	15.2	6.9	6.6
T4	193.3	150.0	138.3	130.5	78.6	70.0	1063.3	998.7	72.4	69.8	17.2	16.2	8.1	7.3
T5	213.0	161.3	151.9	142.3	83.3	74.5	1225.3	1160.3	78.5	73.7	17.7	17.3	9.1	8.3
T6	216.3	165.3	152.9	140.0	83.6	75.6	1268.7	1175.4	78.8	74.5	17.7	17.2	9.1	8.3
T7	181.7	146.3	131.0	121.6	77.2	68.3	856.7	803.6	71.2	68.3	16.6	15.8	7.6	7.0
T8	195.7	152.7	140.5	133.4	78.6	71.1	1080.0	1032.5	73.4	70.3	17.2	16.5	8.2	7.5
T9	187.3	147.3	135.4	126.5	77.9	68.9	926.7	876.3	71.3	68.7	16.7	15.8	7.7	7.0
T10	204.7	157.7	143.8	137.4	80.0	72.8	1165.0	1086.8	77.7	72.8	17.6	17.0	9.0	8.1
S.Em±	6.4	3.9	3.3	2.6	1.5	2.2	36.1	5.8	0.8	1.3	0.6	0.3	0.2	0.2
CD (P=0.05)	19.1	11.7	6.8	7.9	4.5	6.5	107.1	17.3	2.4	3.9	1.9	1.0	0.7	0.7

in plant crop and 50% RDF+ trash @ 10 t ha^{-1} in ratoon crop, respectively. The increase in shoot population in these treatments might be attributed to higher initial germination and tillering in plant crop and higher clump population in ratoon crop due to availability of major nutrients because of better mineralization in T_6 and T_5 and fulfilment of crop requirement due to applied inorganic sources in T_{10}. Kaur and Singh (2021) also reported increased shoot emergence due to INM-induced microbial stimulation.

Dry matter accumulation per shoot

Similar trend as in case of shoot population was followed in dry matter accumulation also. Dry matter accumulation per shoot at 150 DAP was higher in plant crop rather than ratoon crop (Table 2). FYM/ Compost @ 20 t ha^{-1} + inorganic nutrient application

Table 3: Effect of integrated nutrient management on soil fertility status of sugarcane plant-ratoon crop sequence

	Treatments		Organic carbon (%)		Available nitrogen (kg ha^{-1})		Available phosphorous (kg ha^{-1})		Available potassium (kg ha^{-1})	
	Plant	Ratoon	Plant	Ratoon	Plant	Ratoon	Plant	Ratoon	Plant	Ratoon
T1	50% RDF	50% RDF + trash @ 10 t ha^{-1}	0.909	0.902	211.0	206.7	38.0	36.4	217.1	215.8
T2	100% RDF	100% RDF+ trash @ 10 t ha^{-1}	0.912	0.905	212.3	209.3	38.8	37.3	218.2	216.5
T3	NPK on soil test based recommendation	Trash @ 10 t ha^{-1}+ NPK on soil test basis	0.914	0.909	212.8	209.7	39.1	38.3	218.8	217.1
T4	FYM @ 20 t ha^{-1}+ 50% RDF	FYM @ 20 t ha^{-1}+ 50% RDF	1.098	1.086	242.7	238.8	45.8	43.5	248.2	245.7
T5	FYM @ 20 t ha^{-1}+ 100% RDF	FYM @ 20 t ha^{-1}+ 100% RDF	1.102	1.095	246.4	240.1	46.7	44.7	251.4	249.0
T6	FYM @ 20 t ha^{-1}+ NPK on soil test basis	FYM @ 20 t ha^{-1}+ NPK on soil test basis	1.106	1.096	248.6	242.6	47.2	45.8	252.0	250.6
T7	FYM @10 t ha^{-1}+ Biofertilizer + 50% RDF	FYM @ 10 t ha^{-1} + Biofertilizer + 50% RDF	1.045	1.034	235.5	231.2	43.5	40.9	240.6	237.3
T8	FYM @ 10 t ha^{-1}+Biofertilizer +100% RDF	FYM @ 10 t ha^{-1}+Biofertilizer + 100% RDF	1.068	1.058	238.8	233.3	44.7	41.1	242.1	240.6
T9	FYM @ 10 t ha^{-1}+ Biofertilizer+ NPK on soil test basis	FYM @ 10 t ha^{-1}+ Biofertilizer + NPK on soil test basis	1.070	1.062	239.1	235.4	45.0	42.5	244.3	242.2
T10	RDF + 40 kg S + 25 kg $ZnSO_4$	RDF + 40 kg S + 25 kg $ZnSO_4$	0.920	0.916	213.7	210.0	39.5	38.8	219.5	218.8
		S.Em±	0.003	0.005	0.8	0.9	0.9	0.8	0.5	1.1
		CD (P=0.05)	0.010	0.014	2.5	2.7	2.7	2.3	1.3	3.2

based on soil test (T_6) showed significantly higher dry matter accumulation per shoot (152.9 g) as compared to other treatments, being at par with FYM/Compost @ 20 t ha^{-1}+ 100% RDF (T_5) in plant crop, while crop fertilized with FYM/Compost @ 20 t ha^{-1}+ 100% RDF (T_5) exhibited higher dry matter accumulation per shoot (142.3 g respectively), which was at par with FYM/Compost @ 20 t ha^{-1} + inorganic nutrient application based on soil test (T_6) and RDF +S + Zn (T_{10}) in ratoon crop. Treatment T_1- 50% RDF in plant crop and 50% RDF + trash @ 10 t ha^{-1} in ratoon crop exhibited lowest dry matter accumulation (119 and 107.3 g) in plant and ratoon crop, respectively.

The better crop growth under integrated nutrient supply was reflected in terms of higher dry matter accumulation in $T_{6,}$ T_5 and T_{10}. Dry matter accumulation is a function of leaf area index, duration of leaves and efficiency of leaf to convert radiant energy to chemical energy. The higher dry matter accumulation in $T_{6,}$ T_5 and T_{10} might be due to better growth because of luxuriant availability of major nutrients in these treatments. The results are in agreement with the findings of Patel *et al.* (2010) who also reported significant improvement in growth parameters under FYM added plots. As shown by Gupta *et al*. (2020), the synergistic effect of FYM and NPK facilitates better photosynthetic activity and biomass accumulation.

Number of millable canes (NMC)

The results indicated that the application of FYM/ Compost @ 20 t ha^{-1} + inorganic nutrient application based on soil test (T_6) significantly produced the highest number of millable canes (83.6 thousand ha^{-1}), which was at par with FYM/ Compost @ 20 t ha^{-1} + 100% RDF (T_5) and RDF +S + Zn (T_{10}) in plant crop. Whereas, ratoon crop receiving FYM/Compost @ 20 t ha^{-1} + inorganic nutrient application based on soil test (T_6) showed significantly higher number of millable canes (75.6 thousand ha^{-1}), being at par with FYM/ Compost @ 20 t ha^{-1} + 100% RDF (T_5), RDF +S + Zn (T_{10}), FYM/Compost @ 10 t ha^{-1} + Biofertilizer (*Azotobacter/ Acetobacter* + PSB) + 100% RDF (T_8) and FYM/ Compost @ 20 t ha^{-1} + 50% RDF (T_4). Lowest NMC (74.7 and 63.8 thousand ha^{-1}) was recorded with T_1- 50% RDF in plant crop and 50% RDF + trash @ 10 t ha^{-1} in ratoon crop (Table 2). Integration of both organic and inorganic sources of nutrients resulted in improvement in number of millable cane because of improvement in availability of nutrients and less mortality in shoot at harvest in these treatments. This is consistent with observations by Rathore *et al.* (2022), who linked increased millable cane numbers with improved soil nutrient balance under INM practices. Shankaraiah and Kalyanamurthy (2005) also recorded higher yield attributing parameters under integrated nutrient supply.

Individual cane weight

The data (Table 2) revealed that variations in individual cane weight were observed in different treatments. The highest average individual cane weight (1268.7 and 1175.4 g) was recorded in treatment T_6-FYM/Compost @ 20 t ha^{-1} + inorganic nutrient application based on soil test in planted cane and ratoon crop, respectively, which was statistically at par with FYM/ Compost @ 20 t ha^{-1} + 100% RDF (T_5) and RDF +S + Zn (T_{10}) in plant crop and treatment T_5 in ratoon crop. Individual cane weight was higher in these treatments due to the higher cane length and girth. Treatment T_1-50% RDF in plant crop and 50% RDF+ trash @ 10 t ha^{-1} in ratoon crop recorded lowest individual cane weight due to lower cane length and girth, which might be due to poor growth of crop due to unavailability of required nutrients.

Sucrose content

Sucrose content varied significantly due to various integrated nutrient sources applied in planted cane or in ratoon as compared to NPK alone through inorganic sources (table 2). Similar and highest sucrose per cent (17.7%) was recorded with application of FYM/Compost @ 20 t ha^{-1} + inorganic nutrient application based on soil test (T_6) and FYM/ Compost @ 20 t/ha + 100% RDF (T_5) in plant crop. While, significantly higher sucrose per cent (17.3%) was recorded with FYM/ Compost @ 20 t ha^{-1} + 100% RDF (T_5) in ratoon crop. Lowest sucrose content (14.7 and 14.1 %) was exhibited by treatment T_1- 50% RDF (plant crop) and 50% RDF + trash @ 10 t ha^{-1}(ratoon crop) in plant and ratoon crop, respectively. The same results were also in conformity with the findings of Ramalakshmi *et al.* (2011) as they recorded improvement in juice quality parameters when organic along with inorganic fertilizers were applied to the crop and similar to the results of Satyanarayana *et al.* (2023), who reported that FYM and biofertilizer combinations improved sugar recovery.

Cane and Commercial cane sugar yield

Application of 20 t ha^{-1} FYM +soil test based recommendation (T_6) in plant and ratoon crop gave higher cane (78.8 and 74.5 t ha^{-1}) and sugar yield (9.1 and 8.3 t ha^{-1}) in plant and ratoon crop, respectively, being at par with FYM/Compost @ 20 t ha^{-1} + 100% RDF (T_5) and RDF +S + Zn (T_{10}). The cane and sugar yield in above treatment was 15.4 and 13.7% and 49.2 and 43.1% higher than that of recommended NPK in plant and ratoon crop, respectively (table 2). The higher cane yield in these treatments was due to higher NMC and individual cane weight. The higher NMC was due to higher shoot population and which in turn was the result of higher initial emergence and less mortality at harvest. While, higher CCS yield under these treatment was attributed to higher cane yield and higher available sugar in cane. Treatment T_1- 50% RDF (plant crop) and 50% RDF + trash @ 10 t ha^{-1}(ratoon crop) produced lowest cane yield (66.8 and 62.9 t ha^{-1}) and CCS yield (5.9 and 5.5 t ha^{-1}) in plant and ratoon crop, respectively. Results are in conformity with the findings of Kumar *et al.* (2014) and Sinha *et al.* (2014) as they also indicated positive impact of integrated nutrient management on cane and CCS yield due to unrestricted nutrient supply throughout the crop cycle. Gupta *et al.* (2020) and Kumar *et al.* (2018) also observed yield gains under INM systems. Increased yield in these treatments aligns with findings of Kaur and Singh (2021), who emphasized INM's role in maximizing sugarcane productivity.

Soil fertility status

Data pertinent to soil fertility status revealed that variations in organic carbon and available NPK in soil were significant due to different treatments (table 3). The higher organic carbon content (1.106 and 1.096% in plant and ratoon crop, respectively) was recorded in (T_6) FYM/Compost @ 20 t ha^{-1} + inorganic nutrient application based on soil test which was statistically at par with FYM/ Compost @ 20 t ha^{-1}+ 100% RDF (T_5) and FYM/ Compost @ 20 t ha^{-1} + 50% RDF (T_4). However, lower values of organic carbon were recorded in the treatments in which inorganic fertilizers alone was applied.

Crop receiving FYM/Compost @ 20 t ha^{-1} + inorganic nutrient application based on soil test (T_6) showed higher available nitrogen (248.6 and 242.6 kg ha^{-1}) and available potassium (252.0 and 250.6 kg ha^{-1}) in plant and ratoon crop, respectively, which was at par with FYM/Compost @ 20 t ha^{-1} + 100% RDF (T_5). Whereas, significantly higher available phosphorous (47.2 and 45.8 kg ha^{-1}) was recorded in T_6, being statistically at par with T_5, T_9 and T_8 in planted cane and T_5 in ratoon crop. The lowest available nitrogen, phosphorous and potassium was recorded with treatment T_1- 50% RDF in plant crop and 50% RDF+ trash @ 10 t ha^{-1} in ratoon crop. The gain in availability of nutrients in soil due to application of FYM along with chemical fertilizers was due to continuous mineralization of FYM and addition of nutrients through FYM in addition to native nutrients of soil. Impact on availability of phosphorous in soil was also recorded in the treatments in which biofertilizers (*Azotobacter* + PSB) were applied along with FYM @ 10 t ha^{-1} and 100% RDF/ soil test basis recommendation, substantiating results reported by Rathore *et al.* (2022) and ICAR (2020), where long-term INM improved soil health parameters. Biofertilizer use, as highlighted by Satyanarayana *et al.* (2023), also played a significant role in enhancing nutrient availability. Singh and Singh (2002) also reported that soil fertility in terms of organic carbon, available N, P and K could be maintained with use of organic source in combination with chemical fertilizers to meet the nutritional requirements of sugarcane crop.

CONCLUSION

The present study concludes that application of FYM/Compost at 20 t ha{ ¹ combined with soil test-based inorganic nutrient recommendations (T6), or with 100% RDF (T5), significantly improved cane yield, commercial cane sugar (CCS) yield, and soil fertility in sugarcane-ratoon systems. INM approaches not only sustained soil organic carbon and nutrient availability but also enhanced juice quality parameters. Practical recommendations include the adoption of FYM along with precise inorganic fertilizer management based on soil testing for improving productivity sustainably. Future research should focus on multi-year, multi-location studies to further validate these findings and to investigate the impact of INM on soil microbial dynamics and carbon sequestration.

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