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Utilization of Sugarcane and Sugar Industry Wastes for Sustainable Sugarcane Production and Post-Harvest Quality Management

Priyanka Singh[1], Prasoon Kumar[1], Kuldeep Kumar[2] and Sanjay Awasthi[3]
[1]U.P. Council of Sugarcane Research, Shahjahanpur,U.P., India
[2]Dalmia Bharat Sugar and Industries Limited, Sugar Unit -Nigohi Shahjahanpur, U.P., India
[3]The Sugar Technologists' Association of India, New Delhi, India

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ABSTRACT

This four-year collaborative study between STAI, UPCSR, and the Dalmia Bharat and Sugar Industry, Nigohi investigated the utilization of sugarcane and sugar industry by-products and wastes to enhance sugarcane production sustainability. The study was conducted at farmer's fields with sugarcane variety, Co 0118 (early maturing) to explore the impact of sugar mill by-products and inorganic fertilizer application on growth, yield, and quality attributes of plant and ratoon sugarcane. Ten treatments, including inorganic chemicals, organic (sugar industry byproducts and wastes), and integrated fertilizer approaches, were evaluated. The preliminary findings revealed significant variations among treatments, with notable impacts on millable cane numbers and yield. Application of sugarcane industry by-products demonstrated potential in reducing chemical fertilizer needs and improving soil health. Analysis of soil properties and nutrient dynamics showed promising trends, with treatments incorporating compost prepared from sugar mill by-products and biofertilizers leading to enhanced soil organic carbon and microbial populations. Yield attributes, sucrose percentage, and commercial cane sugar (CCS) yield varied across treatments and growth stages, with treatments integrating organic and biofertilizer components showing favourable results. Treatment T6 (PMC at 20t/ha, biofertilizers Azotobacter and PSB at 10 kg/ha each, and irrigation with treated sugar industry wastewater) exhibited the highest yield of 99.2 t/ha, 96.12 t/ha, 86.11 t/ha, and sucrose percentage of 17.22, 18.23, and 18.32 in plant, first and second ratoon crops, respectively. The treatments incorporating by-product utilization and organic inputs exhibit promise for sustainable sugarcane production, enhancing soil fertility, crop yield, and quality while mitigating post-harvest deterioration. These findings emphasize the importance of integrated soil management practices and sugar mill by-product utilization strategies in promoting proper disposal, and reducing the recommended level of chemical fertilizers, thereby enabling improved soil health and sustainable sugarcane cultivation.

Keywords: Sugar industry by-product, PMC, sugar-industry waste, productivity, sustainability, soil health

ABBREVIATIONS

DAP – Days after planting; HR – Hand refractometer; NMC – Number of millable canes; PMC – Press mud cake; PSB – Phosphorous soluble bacteria; RBD – Randomized block design; RDF – Recommended dose of fertilizer; SPMC - Sulphitation press mud cake.

INTRODUCTION

Land productivity has declined due to the consistent use of chemical fertilizers. In India, sugarcane cultivation spans over 5 million hectares of land, where conventional practices involve heavy reliance on chemical fertilizers, herbicides and insecticides to manage yield, weeds and pests. Typically, the nutrient needs of sugarcane are assessed in terms of nitrogen, phosphorus and potassium. However, continuous application of these primary nutrients often leads to a decline in soil organic matter, resulting in the loss of organic carbon, nitrogen, phosphorus, potassium and sulfur from the soil (Singh et al. 2008). The sugarcane

*Corresponding Author email: priyanka.vishen75@gmail.com

and sugar industry yields various by-products such as green tops, trash, bagasse, molasses, filter press mud, fly ash and spent wash, which are commonly regarded as process wastes. Additionally, at the field level, primary wastes including trash, stubbles and residues from intercrops or companion crops, represent substantial quantities. These primary wastes can be processed into organic-rich biomass, which is less environmentally harmful and can effectively enrich the soil (Dotaniya et al. 2016). However, secondary residues or the primary by-products of the sugar industry, such as bagasse, molasses, press mud, bagacillo, fly ash and wastewater, require consistent and careful disposal in an eco-friendly manner.

On an average, processing 100 tonnes of sugarcane in a factory yields approximately 12 tonnes of sugar, 28-30 tonnes of bagasse, 4-5 tonnes of molasses, 3-3.5 tonnes of press mud and 100 m^3 of wastewater in India (Singh and Solomon, 1995). These by-products are rich sources of various chemicals. They can enhance soil organic carbon content, as well as the availability of nitrogen, phosphorus, potassium, sulfur, zinc and manganese to the plants (Elaiya and Elango, 2017). Solid and liquid wastes generated during the crushing, clarification and crystallization processes are abundant in cellulose and micronutrients also. They can be profitably utilized to meet the fertilizer requirements in sugarcane cultivation, thereby improving the economic viability of sugar processing units. Research conducted under diverse agro-climatic conditions has demonstrated the significant potential of sugarcane and sugar mill wastes in enhancing cane productivity and sugar recovery (Singh et al. 2019). Studies by (Singh et al. 2007) indicate that sulphitation press mud cake (SPMC), a sugar factory by-product, contains macro and micronutrients that increase sugarcane yield and maintain soil fertility. The integrated use of SPMC and nitrogen fertilizer has been shown to improve nitrogen use efficiency by 4-8 percent.

Exploring these bio-based by-products not only converts agricultural and factory waste residues into useful bio-products but also holds considerable potential for generating employment opportunities, particularly in rural areas and making sugarcane cultivation more profitable and sustainable. Keeping this in mind, a four-year collaborative study between STAI, UPCSR and the Dalmia Bharat and Sugar Industry, Nigohi was conducted at farmers' fields to assess the potential of recycled sugar mill waste and by-products in replacing the recommended dose of chemical fertilizers in sugarcane cultivation for cost reduction and sustainable production. The comparative analysis involved the application of inorganic chemicals, integrated (inorganic + organic) and organic (sugar industry by-products and wastes) fertilizers concerning sugarcane growth, yield, quality attributes and soil health. The study also evaluated the potential of organic sugar industry by-products and wastes compared to chemical fertilizers in post-harvest quality management.

MATERIALS AND METHOD

Experimental site, layout and time of planting:

The on-farm experiment was laid out on March 20, 2020 (first plant) and on 4 March 2021 (second plant) at Parajarsa village, Nigohi, Shahjahanpur, India. The experiment was in a randomized block design (RBD) with three replications and the plot size was 6 × 10.0 m^2 (6 rows of 10-meter length) approximately.

Sugarcane cultivar and treatments:

The sugarcane cultivar used for this study was Co 0118, an early maturing cultivar. Ten treatments included inorganic chemicals, organic (sugar industry by-products and wastes) and integrated fertilizers as shown in Table 1. The recommended level of fertilizer (RDF) included 180 kg N, 80 kg P_2O_5, 60 kg K_2O and 25 kg $ZnSO_4$ per hectare.

Planting of the experiment and cultural operations

Two-budded cane setts were soaked in 0.1% carbendazim (T1 and T2) and biofertilizer cultures (T3-T10) for 10 minutes before planting. Soil samples were collected before land preparation and formation of planting furrows with a row spacing of 90 cm. Ten treatments (Table 1) were prepared and applied to the furrows. Treatments T1 and T2 (conventional) received one-third of the RDF N and all the required P, K and Zn. Treatments T3 and T4 received one-third of 50% of the RDF N, P and K with PMC (10 t/ha) and biofertilizer (*Azotobacter* + PSB, 10 kg/ha each). The remaining two-thirds of the respective N doses were applied as top dressings in two equal splits before the onset of the monsoon (90 and 120 days after planting (DAP). Treatments T5 to T10 were prepared and applied in the furrows within the respective plots Approximately 5-6 two-budded cane setts (about 10-12 buds) were planted per meter length of furrow in paired rows after application of the treatments. All further cultivation practices were followed with standard procedures including insect pests and disease management as and when required. Light irrigation was applied in the furrows soon after planting with supplementary irrigation as per the treatments (Table 1) with either normal irrigation water (T1, T3, T5, T7 and T9) or sugar-mill treated wastewater (T2, T4, T6, T8 and T10) during the dry period, grand growth phase and whenever required. To protect the cane from lodging, soils were hilled up and the crop propped up at 120 and 150 DAP.

Table 1 : Inorganic chemical, organic (sugar industry by-products and wastes), and integrated fertilizer treatments applied in the experiment

Treatment	Constituents
T_1	Application of nutrients on a soil test basis through chemical fertilizer (100% NPK of RDF) + normal irrigation water
T_2	Application of nutrients on a soil test basis through chemical fertilizer (100% NPK of RDF) + irrigation through sugar industry wastewater (treated)
T_3	Application of PMC @ 10t/ha + 50% NPK of RDF through inorganic + biofertilizers (Azotobactor + PSB) @ 10 kg/ha each + normal irrigation water
T_4	Application of PMC @ 10t/ha + 50% NPK of RDF through inorganic + biofertilizers (Azotobactor + PSB) @ 10 kg/ha each + irrigation through sugar industry wastewater (treated)
T_5	Application of PMC @ 20t/ha + biofertilizers (*Azotobactor* + PSB) @ 10 kg/ha each + normal irrigation water
T_6	Application of PMC @ 20t/ha + biofertilizers (*Azotobactor* + PSB) @ 10 kg/ha each + irrigation through sugar industry wastewater (treated)
T_7	Application of biocompost (PMC + sugarcane tops + trash + bagasse + molasses + fly ash) @ 10t/ha + biofertilizers (*Azotobactor* + PSB) @ 10 kg/ha each + normal irrigation water
T_8	Application of biocompost (PMC + sugarcane tops + trash + bagasse + molasses + fly ash) @ 10t/ha + biofertilizers (*Azotobacto*r + PSB) @ 10 kg/ha each + irrigation through sugar industry waste water (treated)
T_9	Application of biocompost (PMC + sugarcane tops + trash + bagasse + molasses + K- ash) @ 10t/ha + biofertilizers (*Azotobactor* + PSB) @ 10 kg/ha each + normal irrigation water
T_{10}	Application of biocompost (PMC + sugarcane tops + trash + bagasse + molasses + K- ash) @ 10t/ha + biofertilizers (*Azotobactor* + PSB) @ 10 kg/ha each + irrigation through sugar industry wastewater (treated)

Parameters recorded

The first and second plant crops were harvested in February 2021 and 2022 and the first and second ratoon crops in December 2022 and 2023, respectively. Soil samples were collected before planting and after harvesting of the first, second plant crops and first and second ratoon crops. The germination percent was recorded at 45 DAP. Shoot populations were determined at the grand growth and maturing stages. Cane stalks (10 canes per sample in three replications) were used to determine yield attributes, *viz;* cane height, cane girth and cane weight. The number of millable stalks and cane yield were determined by counting and weighing canes per plot. The juice quality attributes, viz brix%, pol%, purity%, CCS% juice and reducing sugars were measured after harvesting of the crop. The reducing sugars in the cane stalk were evaluated by the method of Nelson (1944). Brix% was determined by brix refractometer, for Pol% juice analysis the fresh cane juice was cleared by adding 0.6 g lead acetate in 100 mL cane juice and after shaking for a few minutes it was filtered through Whatman filter paper no 1 and Pol% juice was determined in clear juice by a Rudolph Automatic Polarimeter. The CCS%

(juice) = 1.022 Pol% juice – 0.292 0Brix formula was used to determine the commercial cane sugar percentage in juice.For the assessment of post-harvest quality deterioration, the canes of uniform size from each treatment (T1-T10) were harvested, topped and detrashed during April/May (2021-24) and kept in two separate bundles under open field conditions in three replicates (Figure 1a, b and c). The first heap was kept open and used as control (R1) the second heap was mist-sprayed with water and covered with a thick layer of trash (R2). Ten canes from each heap were selected randomly and juice was extracted at 0, 48, 96, 144, 192 and 240 hours respectively. The deterioration in cane quality of each treatment was assessed by observing moisture loss, brix, pol% juice, CCS%, invertase activities and dextran. The data was determined in three replications. The data presented are the mean of two plant crops (plant crops in 2020-21 and 2021-22), the first ratoon (2022-23) and the second ratoon crop (2023-24).

Figure 1a : Harvesting of the canes for quality and pos harvest analysis

Figure 1b : Canes kept under open field conditions (R1)

Figure 1c : Canes kept under the trash-covered condition (R2)

RESULTS AND DISCUSSION

Studies on soil physio-chemical properties

The data observed before and after planting and after the harvesting of the plant, first and second ratoon found that there are notable changes in soil properties and nutrient contents across different treatments and stages of the experiment. The pH levels showed a significant increase from 6.9 before planting to 7.77 after harvesting the plant crop, indicating a 12.61% increase. Across the first harvest, first ratoon crop and second ratoon crop stages, the organic carbon content in the soil displayed varied trends among treatments. In the first harvest, treatments T3 to T6 exhibited substantial increases in organic carbon content, ranging from 74.60% to 114.29%, while T1 and T2 experienced minor decreases. However, in the first ratoon crop, T5 and T6 showed notable increases, with T6 recording the highest rise of 90.48% followed by T5 by 85.71%, whereas T1 and T2 saw declines. During the second ratoon crop, treatments T5 and T6 continued to demonstrate significant increases, while most other treatments experienced decreases in organic carbon content (Tables 2a, c, d, e). Although there was a slight decline in the organic carbon content in the soil after the harvest of the second ratoon crop as compared to the organic carbon content increase after the harvest of plant cane, the overall organic carbon content was found to increase as compared to the initial soil carbon content by 26.98% (T9) to 85.71% (T6). The fluctuations can be attributed to factors such as organic matter decomposition and microbial activity. The initial total microbial counts of the soil before the planting was 1.09x108cfu/g (mean of two plants), however, after the harvesting of plant cane, there was a slight increase in the total microbial counts in the treatments T3 to T10 where the compost was applied, the total microbial count in ten different treatments ranged from 1.13×10^8 to 1.73×10^8 cfu/g. Treatments T5 and T6 displayed the highest microbial counts among all treatments. After the harvest of the first ratoon crop, significant increases in microbial counts were observed across treatments compared to the plant crop stage, with values ranging from 1.2×10^8 cfu/g to 1.12×10^9 cfu/g. Treatments T5, T6, T9 and T10 exhibited notably higher microbial counts compared to other treatments. Microbial counts continued to increase substantially across treatments, after the harvest of the second ratoon crop with values ranging from 1.31×10^8 cfu/g to 3.78×10^9 cfu/g. Treatments T5, T6, T8 and T10 particularly showed the highest post-treatment microbial counts, indicating that these treatments may have been particularly effective in enhancing microbial populations (Tables 2b and f).

The analysis of soil physio-chemical properties revealed significant impacts of various treatments on soil characteristics. Incorporating organic materials like pressmud compost and biofertilizers positively influenced soil tilth, fertility and productivity. Pressmud compost enhances soil texture, structure, water retention and drainage capacity, improving soil aggregate stability and ammonifying capacity (Kumar et al. 2017). Moreover, it contributed to increased soil organic matter content, promoting nutrient availability and crop yield. Chemical properties analysis indicated notable changes in soil pH, electrical conductivity and nutrient levels across treatments and stages. Treatments incorporating compost and biofertilizers exhibited higher pH values and reduced salt content, while potassium levels notably increased, indicating enhanced nutrient availability. Additionally, the study observed fluctuations in organic carbon content, microbial populations and their correlation with treatments. Incorporating organic amendments and biofertilizers stimulated microbial proliferation, leading to increased organic carbon levels and improved soil health and fertility (Mahmud et al. 2021). These findings stresses on the potential of organic inputs in promoting sustainable soil management practices and enhancing crop productivity in sugarcane cultivation systems. However, further validation through field studies may provide more definitive conclusions.

Table 2a : Soil-chemical properties before planting

pH dsm^{-1}	E.C %	C kg/ha	P kg/ha	K kg/ha	S mg/kg	Zn mg/kg	Fe mg/kg	Mn mg/kg	Cu
6.9	0.270	0.63	8.2	141.12	18.35	2.20	17.81	4.6	0.692

Table 2b : Total microbial population and bulk density of the field before planting

Total microbial count (cfu/gm)	Bulk density (kg/m^3)
1.09 x 108	1.18

Table 2c : Soil-test values of samples collected after the harvest of the plant crop

Treatment	pH	E.C dsm^{-1}	C %	P kg/ha	K kg/ha	S kg/ha	Zn mg/kg	Fe mg/kg	Mn mg/kg	Cu mg/kg
T_1	7.03	0.247	0.60	8.50	139.53	17.2	1.71	17.69	4.30	1.21
T2	7.04	0.237	0.61	8.63	129.03	16.5	2.37	17.35	3.10	1.13
T3	7.40	0.224	1.10	9.50	145.00	16.3	2.52	13.68	3.20	1.24
T4	7.60	0.198	1.12	9.20	148.40	16.0	2.92	13.14	3.43	1.11
T5	7.53	0.168	1.33	8.80	152.20	17.4	2.84	19.39	4.70	1.16
T6	7.63	0.159	1.35	8.47	151.30	17.5	2.24	18.88	4.07	1.24
T7	7.57	0.167	1.12	8.70	153.23	18.3	2.27	18.44	3.97	1.07
T8	7.67	0.190	1.09	9.80	159.50	16.5	2.41	19.01	3.87	1.16
T9	7.73	0.201	1.15	9.67	248.53	16.2	2.81	19.07	3.50	1.26
T10	7.77	0.196	1.10	7.93	224.83	16.3	2.24	19.78	3.80	1.12

Table 2d : Soil-test values of samples collected after the harvest of the 1st ratoon crop

Treatment	pH	E.C dsm^{-1}	C %	P kg/ha	K kg/ha	S kg/ha	Zn mg/kg	Fe mg/kg	Mn mg/kg	Cu mg/kg
T_1	7.2	0.245	0.57	8.6	150.4	18.5	1.86	14.25	4.2	2.40
T_2	7.2	0.250	0.60	8.2	158.0	19.0	2.40	14.00	3.3	1.75
T_3	7.4	0.198	0.95	8.7	162.8	17.5	2.27	13.49	6.0	2.47
T_4	7.5	0.170	0.91	9.3	168.9	18.2	2.18	13.92	4.2	1.73
T_5	7.7	0.146	1.17	9.7	198.6	18.7	2.99	12.29	4.6	1.73
T_6	7.3	0.167	1.20	9.4	206.0	18.8	2.82	13.88	4.4	1.53
T_7	7.4	0.150	0.91	8.7	208.3	17.6	2.17	14.25	6.4	1.04
T_8	7.4	0.175	0.91	8.8	191.2	16.6	2.09	13.96	4.8	0.93
T_9	7.4	0.188	0.82	8.7	257.6	17.8	2.95	14.13	4.8	0.91
T_{10}	7.3	0.145	0.85	9.5	185.9	19.0	2.42	13.83	6.0	1.59

Table 2e – Soil-test values of samples collected after the harvest of the 2nd ratoon crop

Treatment	pH	E.C dsm^{-1}	C %	P kg/ha	K kg/ha	S kg/ha	Zn mg/kg	Fe mg/kg	Mn mg/kg	Cu mg/kg
T_1	7.7	0.258	0.58	8.5	148.1	7.0	1.94	11.56	1.35	1.21
T_2	7.6	0.257	0.63	8.6	152.6	8.5	1.92	12.40	1.26	1.90
T_3	7.7	0.167	0.93	7.1	160.1	9.0	1.28	10.42	1.32	1.44
T_4	7.7	0.177	0.94	7.5	168.6	7.5	1.63	10.16	1.44	1.38
T_5	7.8	0.160	1.14	10.2	197.2	8.5	0.83	12.96	3.12	0.58
T_6	7.6	0.145	1.17	10.8	192.1	7.8	1.16	11.21	1.57	0.45
T_7	7.7	0.165	0.87	8.8	197.2	9.5	1.09	13.25	2.72	0.81
T_8	7.6	0.178	0.89	9.0	193.9	6.8	1.32	14.48	2.02	0.96
T_9	7.6	0.195	0.80	8.7	280.6	8.5	1.12	14.16	2.11	0.81
T_{10}	7.6	0.187	0.83	9.1	273.9	8.5	1.00	13.08	2.60	0.79

Table 2f : Total microbial population of the soil after the harvest of plant crop, 1st ratoon crop, and 2nd ratoon crop

Treatments	Total Microbial Count (cfu/gm)		
	Plant crop	1st Ratoon crop	2nd Ratoon crop
T_1	$1.13x10^8$	$1.5x10^8$	$1.5x10^8$
T_2	$1.14x10^8$	$1.2x10^8$	$1.31x10^8$
T_3	$1.42x10^8$	$4.5x10^8$	$1.29x10^9$
T_4	$1.48x10^8$	$4.3x10^8$	$1.16x10^9$
T_5	$1.71x10^8$	$1.11x10^9$	$3.78x10^9$
T_6	$1.73x10^8$	$1.12x10^9$	$3.73x10^9$
T_7	$1.56x10^8$	$8.1x10^8$	$2.67x10^9$
T_8	$1.65x10^8$	$8.7x10^8$	$2.97x10^9$
T_9	$1.62x10^8$	$1.02x10^9$	$2.88x10^9$
T_{10}	$1.66x10^8$	$1.04x10^9$	$3.14x10^9$

Impact of inorganic chemical, organic (sugar industry by-products and wastes), and integrated fertilizer treatments on growth and yield parameters:

The examination of growth parameters provided valuable insights into the efficacy of different treatments in optimizing sugarcane production across plant cane, first ratoon, and second ratoon crops. Germination rates varied slightly across treatments, with T6 displaying the highest rate at 56.73%, followed closely by T5. Regarding tiller counts, T4 exhibited the highest number per hectare (142,596) in plant cane, while T6 demonstrated the highest tiller count in both first (127,651/ha) and second (110,002/ha) ratoon crops. Similarly, T6 consistently showed the highest number of millable canes (NMC) across plant and ratoon canes, with a maximum of 102,225 NMC/ha in plant cane, 97,484 NMC/ha in the first ratoon, and 92,595 NMC/ha in the second ratoon. Additionally, treatments incorporating PMC and biofertilizers, demonstrated promising results for NMC, highlighting their role in sustaining cane productivity over successive crop cycles. Yield analysis revealed significant variations among treatments, with T6 consistently producing the highest yields across all cane types, with a maximum of 99.2 t/ha in plant cane, 96.12 t/ha in the first ratoon, and 86.11 t/ha in the second ratoon. Treatments T5, T3, and T4 also showed promising results, indicating the effectiveness of PMC, biofertilizers, and irrigation practices in enhancing sugarcane productivity. An earlier study conducted by Yadav (2004) indicates that combining press mud cake with nitrogen fertilizer resulted in a 4-8 percent increase in nitrogen use efficiency. Additionally, studies have shown that the inclusion of beneficial microorganisms such as Azotobacter, and PSB, can reduce the need for nitrogen fertilizer by over 25 percent in sugarcane cultivation (Nosrati et al. 2014). This shows the significant role of press mud and biofertilizers in optimizing nitrogen use efficiency in sugarcane farming Yadav (2004). Moreover, it has been recommended that an integrated approach to nutrient management be adopted, utilizing a combination of organic, inorganic, and bio-fertilizers in a balanced and coordinated manner to maintain soil fertility and enhance productivity (Tayade et al. 2022). These findings further emphasize the importance of integrated nutrient management and sustainable irrigation practices in optimizing sugarcane yield and productivity (Table 3).

***Impact of inorganic chemical, organic (sugar industry by-products and wastes), and integrated fertilizer treatments on quality parameters* :**

The analysis of sugarcane juice parameters reveals variations in sugar content and quality among treatments. Brix values, varied between 18.50 and 19.86 in plant cane, with treatments containing biocompost and biofertilizers showing higher values, particularly in the first ratoon crop. Sucrose percentages ranged from 16.24% to 17.22%, with treatments incorporating biocompost and biofertilizers consistently exhibiting higher sucrose percentages, especially in the first ratoon cane. Purity coefficients, representing the proportion of sucrose to other soluble solids, also varied among treatments, with the same trend. A study by Abhishek et al. 2020 also shows that the sulphitation press mud has been found to increase the population, length, and girth of millable cane and also, improve sucrose content in cane juice in comparison to inorganic fertilizers. Similarly, CCS% ranged from 11.08% to 11.80% in plant cane, however, CCS yield per hectare varied between 9.8 t/ha and 11.7 t/ha, with treatments incorporating biocompost and biofertilizers consistently demonstrating higher values (Table 4). In the first and second ratoon cane, similar trends were observed, variations in sugar content and yield were evident across treatments, with treatments displaying higher CCS% and CCS yield per hectare, particularly those with biocompost and biofertilizers. Overall, these findings highlight the potential of integrated soil management practices, particularly those involving biocompost and biofertilizers, in enhancing sugarcane juice quality and maximizing sugar extraction efficiency across different growth stages. These findings align with a study conducted by Sinha et al. (2016) demonstrating that the incorporation of bio-compost, either alone or in combination with inorganic fertilizer-N, substantially enhances both sugarcane and sugar yields, as well as the organic carbon content in the soil (Table 4).

The growth, yield, and quality data observed for plant cane, first and second ratoon demonstrates that treatments incorporating organic and biofertilizer components, such as treatment T6 (involving PMC at 20t/ha, biofertilizers Azotobactor and PSB at 10 kg/ha each, and irrigation with treated sugar industry wastewater) and treatment T5 (comprising PMC at 20t/ha and biofertilizers Azotobactor + PSB at 10 kg/ha each with normal irrigation water), exhibit significant advantages in terms of yield attributes, including the number of tillers, number of millable canes, cane yield, and sugar yield. Notably, treatment T4 (integrating chemical and organic fertilizer) also emerges as a favourable option. These treatments contribute to improvements in soil quality, as evidenced by positive responses in soil organic carbon and other soil health indicators. However, the study highlights the importance of integrating soil management practices and sugar industry by-product utilization strategies to enhance sugarcane cultivation's productivity, profitability, and environmental sustainability. Treatments T3, T4, T5, and T6 emerge as promising approaches for sustainable sugarcane production (Table 3 and 4).

Assessment of post-harvest quality deterioration in plant, 1st ratoon, and 2nd ratoon canes

The study also extended to evaluate the impact of various treatments (T1-T10) on the post-harvest quality of sugarcane stored under high-temperature conditions (April/May)for 240 hours, focusing on moisture loss, sucrose content, commercial cane sugar (CCS) percentage, reducing sugar levels, dextran content, and invertase activity across plant cane, first ratoon cane, and second ratoon cane. Treatment T6 (PMC @ 20t/ha + biofertilizers + irrigation through sugar industry wastewater) consistently demonstrated the best results, with the lowest moisture loss (plant cane: R1 30.26%, R2 25.43%; first ratoon: R1 25.40%, R2 23.28%; second ratoon: R1 30.42%, R2 27.33%), and minimal sucrose degradation (plant cane: R1 3.21-3.33 units, R2 3.12-3.14 units; similar trends for ratoon canes).

Least CCS% loss (plant cane: R1 4.45%, R2 4.20%; first ratoon: R2 3.65-3.67%; second ratoon: R2 5.74-5.83%), lowest reducing sugar levels (plant cane: R1 9.6-105.2 mg/ml, R2 9.6-99.8 mg/ml; first and second ratoon canes showed similar trends), lowest dextran content (plant cane: R1 138.7-188.3 mg/l, R2 138.7-182.7 mg/l; similar trends for ratoon canes), and reduced invertase activity (plant cane: R1 6.08 µmol, R2 4.95 µmol; first ratoon: R1 6.00 µmol, R2 5.23 µmol; second ratoon: R1 6.92 µmol, R2 6.25 µmol) was observed in T6 compared to other treatments (Figure2 a-f). However, treatment T1 (100% NPK of RDF + normal irrigation water) and T2 (100% NPK of RDF + irrigation through sugar industry wastewater) showed the highest deterioration rates. T2 had the highest moisture loss (plant cane: R1 30.86%, R2 26.09%; first ratoon: R2 28.30%), and T1 had the highest moisture loss for second ratoon cane (R1 31.65%). For sucrose content, T1 and T2 consistently showed higher losses. The highest CCS% loss was observed in T1 and T2 (plant cane: R1 4.67-4.73%; first ratoon: R1 4.76-4.77%; second ratoon: R1 6.20-6.32%). T1 also showed the highest reducing sugar levels (plant cane: R1 10.9-105.8 mg/ml, R2 10.9-99.8 mg/ml; first ratoon: R1 12.7-110.8 mg/ml, R2 12.7-101.2 mg/ml; second ratoon: R1 11.9-108.9 mg/ml, R2 11.9-106.4 mg/ml). Additionally, T1 had the highest

Table 3 : Effect of different treatments on yield attributes of plant cane (mean of two years 2020-22), 1st ratoon cane (2022-23) and 2nd ratoon cane (2023-24)

Treat ments	Germin ation %	Tillers (000/ha)			Millable stalks (000/ha)			Cane length (cm)			Stalk weight (kg)			Cane Yield (t/ha)		
	Plant cane	Plant cane	1st ratoon cane	2nd ratoon cane	Plant cane	1st ratoon cane	2nd ratoon cane	Plant cane	1st ratoon cane	2nd ratoon cane	Plant cane	1st ratoon cane	2nd ratoon cane	Plant cane	1st ratoon cane	2nd ratoon cane
T_1	52.38	132.78	117.26	101.29	91.133	88.61	83.33	255	243	255	1.21	1.17	1.50	95.4	85.98	80.00
T_2	51.18	123.15	119.05	97.40	92.78	90.04	80.55	249	248	260	1.20	1.15	1.54	93.6	87.55	79.08
T_3	54.17	134.07	125.70	101.11	97.59	95.05	84.26	245	243	235	1.12	1.14	1.56	98.2	90.04	82.41
T_4	52.97	142.59	126.05	95.18	97.78	95.62	90.74	260	252	238	1.15	1.14	1.47	98.6	90.74	81.11
T_5	55.95	135.37	126.15	106.11	97.04	96.73	92.22	240	250	242	1.14	1.22	1.52	96.2	94.12	85.00
T_6	56.73	139.63	127.65	110.00	102.22	97.48	92.59	243	254	245	1.18	1.35	1.60	99.2	96.12	86.11
T_7	53.37	118.33	118.55	99.81	84.81	89.07	87.03	244	248	243	1.17	1.33	1.55	89.3	84.96	80.92
T_8	53.76	133.70	118.18	99.07	94.26	90.06	91.66	263	251	240	1.14	1.24	1.53	91.6	84.68	81.48
T_9	51.58	107.22	101.94	97.03	82.41	79.75	81.48	225	226	238	1.18	1.22	1.48	87.9	87.30	78.52
T_{10}	50.88	109.44	102.90	99.26	89.07	80.71	80.0	232	236	235	1.20	1.24	1.45	90.4	87.14	78.15
C.V	2.63	0.001	0.003	0.007	0.001	0.002	0.004	0.63	9.24	10.89	1.13	22.3	28.75	0.58	0.61	3.52
S.E	1.76	1.79	0.296	6.14	1.31	1.40	3.30	1.26	18.42	21.62	0.01	0.21	0.36	0.44	0.44	2.34
C.D	3.71	3.77	0.623	NS	2.76	29.59	6.93	2.65	NS	NS	0.02	NS	NS	0.93	0.93	4.91

Table 4 : Impact of different treatments on quality attributes of plant cane (mean of two years, 2020-22), 1st ratoon cane (2022-23) and 2nd ratoon cane (2023-24)

Treatment	^{0}Brix			Sucrose %			Purity coefficients			CCS %			CCS t/ha			Reducing sugars (mg/ml)		
	Plant cane	1^{st} ratoon cane	2^{nd} ratoon cane	Plant cane	1^{st} ratoon cane	2^{nd} ratoon cane	Plant cane	1^{st} ratoon cane	2^{nd} ratoon cane	Plant cane	1^{st} ratoon cane	2^{nd} ratoon cane	Plant cane	1^{st} ratoon cane	2^{nd} ratoon cane	Plant cane	1^{st} ratoon cane	2^{nd} ratoon cane
T_1	19.5	20.5	20.1	16.9	18.0	17.8	86.5	88.0	88.3	11.5	12.4	12.3	11.0	10.7	9.8	2.3	5.8	10.0
T_2	19.4	20.6	20.1	16.7	18.2	17.72	86.3	88.1	88.1	11.4	12.5	12.2	10.7	11.0	9.6	2.3	6.0	9.1
T_3	19.2	20.5	20.0	16.6	18.0	17.6	86.2	87.9	88.1	11.3	12.4	12.2	11.1	11.1	10.0	6.1	6.7	8.1
T_4	18.9	20.5	20.1	16.3	18.0	17.8	85.9	87.7	88.8	11.1	12.4	12.4	10.9	11.2	10.0	5.2	6.6	8.4
T_5	18.9	20.9	20.2	16.2	18.4	17.9	85.9	87.9	88.8	11.0	12.7	12.4	10.6	11.9	10.5	3.5	4.5	5.9
T_6	19.8	20.5	20.3	17.2	18.2	18.32	86.7	88.5	89.8	11.8	12.6	12.7	11.7	12.1	11.0	4.1	4.0	5.7
T_7	19.5	20.9	20.2	16.8	18.6	18.1	86.1	88.9	89.7	11.6	12.9	12.6	10.4	10.9	10.2	4.0	4.7	6.8
T_8	19.5	21.1	20.3	16.9	18.8	18.2	86.6	89.1	89.8	11.6	13.1	12.7	10.6	11.1	10.3	3.0	5.1	6.0
T_9	19.0	20.3	20.2	16.3	17.7	18.1	86.0	87.4	89.4	11.1	12.2	12.6	9.8	10.6	9.9	4.0	5.6	6.1
T_{10}	19.1	20.6	20.2	16.4	18.1	18.1	86.0	87.6	89.3	11.2	12.4	12.5	10.1	10.8	9.8	5.4	6.1	7.0
C.V.	1.1	2.3	2.3	3.3	2.8	2.8	0.73	4.1	4.1	0.61	4.6	1.1	3.8	4.8	3.8	3.9	19.9	15.0
S.E.	0.17	0.39	0.39	0.45	0.42	0.42	0.52	2.96	3.05	0.06	0.47	0.11	0.32	0.45	0.32	0.13	0.90	0.90
C.D.	0.36	NS	NS	0.95	NS	NS	NS	NS	NS	0.12	NS	NS	NS	NS	NS	0.27	NS	1.90

dextran content (plant cane: R1 181.9-232.1 mg/l, R2 181.9-228.0 mg/l; first ratoon: R1 190.8-240.1 mg/l, R2 190.8-236.4 mg/l; second ratoon: R1 186.5-235.0 mg/l, R2 186.5-233.9 mg/l). Finally, T2 exhibited the highest invertase activity (plant cane: R1 6.32 µmol, R2 5.07 µmol; first ratoon: R1 6.95 µmol, R2 5.92 µmol; second ratoon: R1 7.65 µmol, R2 6.99 µmol) (Figure 2a – f).

Treatment T6 was the most effective in maintaining the post-harvest quality of sugarcane across all parameters. However, treatments T1 and T2, which relied solely on chemical fertilizers, were less effective, showing higher rates of deterioration. Trash covering of the canes (R2) generally helped in reducing quality degradation compared to open storage (R1).

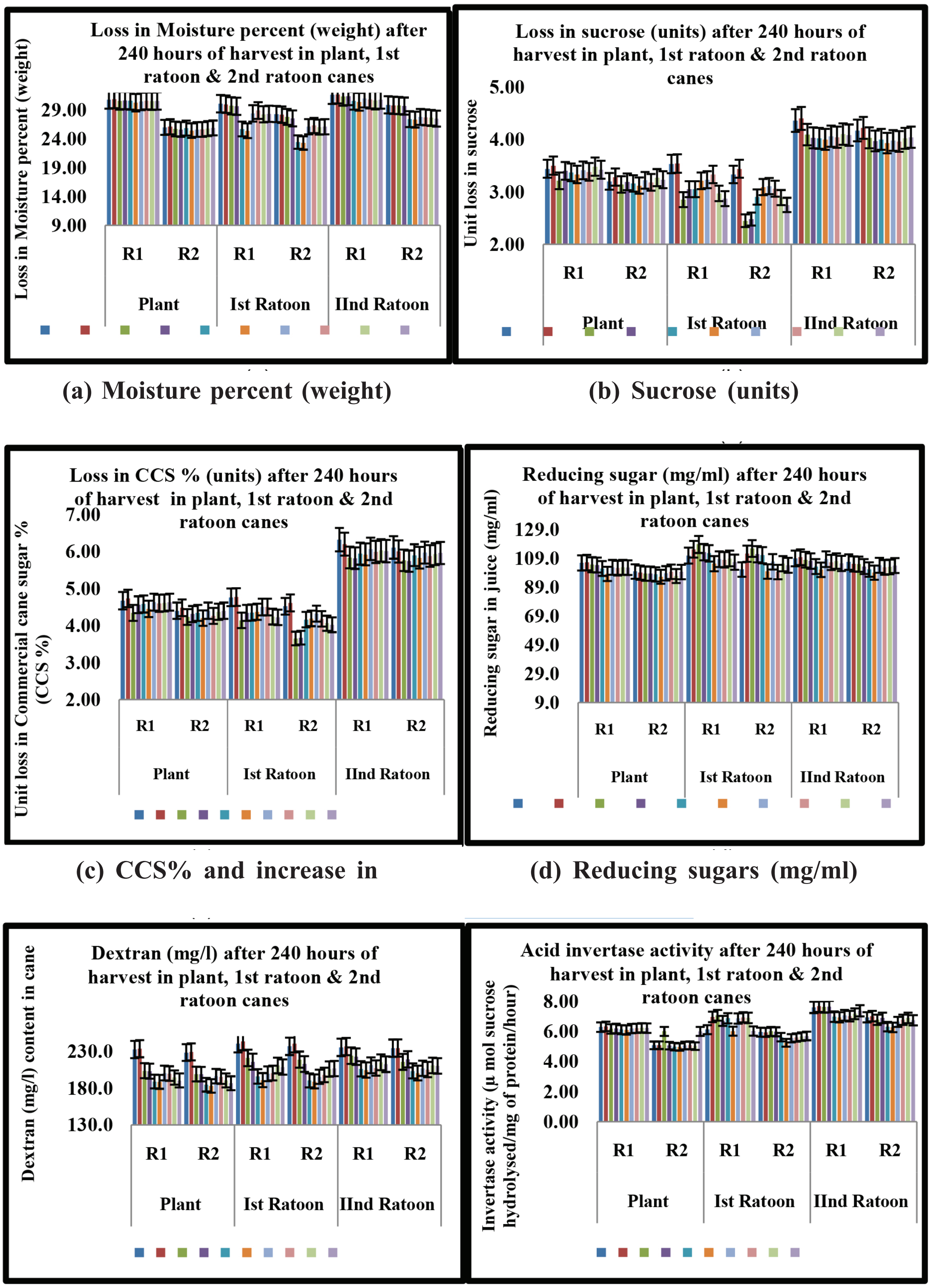
Table 5 : The average minimum, maximum temperature, and relative humidity (Shahjahanpur, India)

Month	Temperature (^{0}C)		RH %	Rainfall (mm)
	Maximum	Minimum		
2021-22				
April	40.6	22.9	46	Nil
May	37.9	24.8	52	36.0
2023				
April	34.9	19.9	46	39.0
May	37.1	22.9	52	12.4
2024				
April	37.1	21.6	40	9.4

These findings emphasise combining organic treatments and biofertilizers in maintaining sugarcane quality post-harvest, particularly under high-temperature conditions. The bulky organic manures from the sugar industry by-products and waste containing almost all the macro and micronutrients provide congenial soil-water relations for better nutrient release and availability Singh et al. (2018). Press mud benefits crops' growth and yield through direct, residual, and cumulative effects. Integrated use of organic sugar industry wastes and chemical fertilizer has been found to increase the population, length, and girth of millable cane and improve sucrose content in cane juice compared to inorganic fertilizers Abhishek et al. (2020). However, the organic content in soil produces quality raw material that reduces losses post-harvest. The findings show that the quality deterioration was less in canes where PMC, fly ash, and biofertilizers were applied compared to only chemical fertilizers applied in canes. Balanced use of the sugar industry, organic by-products other recommended biofertilizers, and appropriate plant protection measures will ensure a healthy crop stand with high sugar content and less post-harvest sugar deterioration. Nevertheless, as sugarcane deteriorates with time after harvest, it is essential to transport cane to the mill as soon as possible, especially during high temperatures.

CONCLUSION

The study highlights the superiority of treatments incorporating organic matter, biofertilizers, and sugarcane industry by-products and wastes over those relying solely on chemical fertilizers. Utilizing waste materials alongside biofertilizers enhances soil fertility, resulting in higher yields and superior quality parameters. These strategies enrich the soil and positively influence the growth, yield, and quality attributes of sugarcane by facilitating nutrient retention. Treatments emphasizing waste utilization consistently outperform others regarding yield, CCS% content, CCS yield (t/ha), and sucrose content, showcasing the efficacy of integrated soil management. Adopting such practices economically reduces chemical input dependency, enhances productivity and contributes to environmental conservation. Integrated soil management approaches are essential for ensuring sustainable sugarcane



(a) Moisture percent (weight)

(b) Sucrose (units)

(c) CCS% and increase in

(d) Reducing sugars (mg/ml)

(e) Dextran (mg/l)

(f) Acid invertase activity

Figure 2 : Post harvest loss after 240 hours in plant cane (2021-22) 1st ratoon cane (2023) and (c) 2nd ratoon cane (2024) during April/May (high temperature)

production. Future research should focus on assessing the long-term effects of these treatments under varying conditions, while extension programs should promote their adoption among farmers.

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