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Enhancing Ratoon Sugarcane Juice Quality and Sugar Recovery through Integrated Soil and Water Management

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ABSTRACT

Background: Ratoon sugarcane production reduces establishment costs but may be affected by declining soil fertility and inadequate irrigation, resulting in reduced juice quality and sugar recovery.
Objective: This study evaluated the effects of integrated soil and water management on juice quality and sugar recovery of ratoon sugarcane (Saccharum officinarum L.) clone CP-249.
Methods: The experiment was conducted at the Abdul Wali khan university, Mardan, Pakistan, during 2022–2024 using a randomized complete block design with split-plot arrangement and three replications. Three irrigation regimes (100%, 75%, and 50% of recommended irrigation) were combined with four soil amendment treatments: control, press-mud, polymer-coated SSP, and 50% cane-trash boiler ash + 50% SOP. Brix, Pol, fiber, commercial cane sugar (CCS), and cane sugar recovery (CSR) were determined, and treatment means were compared using Tukey's HSD test at $p \leq 0.05$.
Results: Irrigation and soil amendments significantly affected juice quality and sugar recovery. Full irrigation produced the highest Brix (21.84%), Pol (18.73%), CCS (13.56%), and CSR (12.75%). Press-mud resulted in the highest Brix (22.18%), Pol (19.11%), CCS (13.94%), and CSR (13.10%) and the lowest fiber content (11.09%). The combination of full irrigation and press-mud produced the highest CCS (14.89%) and CSR (14.00%).
Conclusion: Integrated management, particularly full irrigation combined with press-mud, effectively improved ratoon sugarcane juice quality and sugar recovery.

Keywords: Ratoon sugarcane; Irrigation; Soil amendments; Juice quality; Sugar recovery

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INTRODUCTION

Sugarcane (Saccharum officinarum L.) is an important commercial crop cultivated extensively in tropical and subtropical regions and is a major source of sucrose, ethanol, bioenergy, and numerous industrial by-products [1,2,3]. Because of its high biomass production and sucrose accumulation capacity, sugarcane has considerable economic importance for both farmers and sugar-processing industries [4,5]. Pakistan is also highly dependent on sugarcane as an important cash crop; however, its production is constrained by inadequate irrigation, inefficient input use, low-yielding cultivars, pest and disease pressure, and soil fertility problems [6]. Irrigation water, fertilizers, and other production inputs constitute major components of sugarcane production costs, making efficient resource management essential for improving profitability and sustainability [7,8]. Ratoon cultivation is an important production system in sugarcane in which the crop regenerates from the underground stubble remaining after harvesting [9]. Compared with plant-cane establishment, ratooning can reduce expenses associated with land preparation, seed cane, planting, and crop establishment [10]. Nevertheless, repeated ratooning can result in nutrient depletion, deterioration of soil conditions, reduced root activity, and declining crop performance if appropriate management practices are not adopted [11]. Maintaining adequate nutrient and water availability is therefore particularly important for ratoon crops [12]. Effective management can support tillering, stalk development, photosynthesis, carbohydrate translocation, and sucrose accumulation, ultimately improving both cane quality and recoverable sugar [13,14]. Water availability is one of the major factors determining sugarcane growth and productivity [15]. Sugarcane requires substantial amounts of water because of its high biomass production and extended growing period [16]. Water deficit can reduce leaf expansion, stalk elongation, photosynthesis, biomass accumulation, and ultimately sucrose production [17,18]. Research has demonstrated that sugarcane responds differently to water stress according to its developmental stage and the severity and duration of the deficit [19,20]. Under increasing soil-water deficit, reductions may initially occur in leaf and stalk extension, followed by effects on biomass accumulation and sucrose accumulation [21]. Therefore, irrigation management should aim not simply to maximize water application but to provide sufficient moisture during critical growth stages while avoiding unnecessary water use [22]. Soil fertility is another major determinant of ratoon sugarcane performance [23]. Continuous cultivation and repeated removal of cane biomass can progressively reduce the availability of essential nutrients [24]. Integrated application of organic and mineral soil amendments can improve nutrient availability while also contributing to better soil physical and biological properties [25]. Press-mud, a by-product of sugar processing, contains organic matter and plant nutrients and represents a potentially valuable amendment for improving soil fertility and recycling nutrients within sugarcane production systems [26]. Its application can potentially improve soil structure, nutrient availability, microbial activity, and water-holding capacity, thereby supporting ratoon crop growth. [11] Phosphorus and potassium are particularly important nutrients for sugarcane [27]. Phosphorus contributes to root development, energy transfer, and metabolic processes, whereas potassium plays important roles in water regulation, enzyme activation, photosynthesis, and carbohydrate transport [12]. Because sucrose accumulation depends on the coordinated production, transport, and storage of carbohydrates, adequate nutrient availability is essential for achieving desirable juice quality [4]. Sucrose accumulation in sugarcane is a complex physiological process regulated by multiple enzymes, transporters, and metabolic pathways rather than by a single factor [18]. Polymer-coated single super phosphate (SSP) may improve phosphorus-use efficiency by providing nutrients progressively, while cane-trash boiler ash can contribute mineral nutrients and SOP provides potassium [28]. Consequently, combining organic and mineral amendments may provide complementary benefits for ratoon sugarcane nutrition [25]. Juice quality is particularly important because cane yield alone does not determine the quantity of sugar obtained during processing [29]. Brix represents the soluble-solids concentration of cane juice, while Pol provides an estimate of sucrose concentration [30]. Fiber content is also important because excessive fiber can influence juice extraction efficiency [31]. Commercial cane sugar (CCS) and cane sugar recovery (CSR) therefore provide useful measures of the potential quantity of sugar recoverable from harvested cane [32]. Irrigation and nutrient management can influence these parameters by modifying plant growth, sucrose accumulation, juice concentration, and fiber formation [8]. Studies have shown that irrigation practices can alter sugarcane yield and quality, although the response depends on environmental conditions, crop stage, and the magnitude of water stress [21]. The interaction between irrigation and soil fertility management is particularly relevant under water-limited conditions [28]. Adequate soil moisture facilitates nutrient dissolution and uptake, while improved soil structure and nutrient status can enhance root development and water-use efficiency [33]. Conversely, severe water deficit may restrict nutrient uptake and reduce the effectiveness of fertilizer applications [34]. Thus, integrated management of soil amendments and irrigation may provide a more sustainable approach than managing either factor independently [28]. Despite the importance of sugarcane in Pakistan, relatively limited information is available on the combined effects of irrigation regimes and alternative soil amendments on the quality of ratoon cane juice and sugar recovery under the agroecological conditions of Faisalabad [35]. Therefore, the present study was conducted to evaluate the effects of different irrigation levels and soil amendments, including press-mud, polymer-coated SSP, and cane-trash boiler ash combined with SOP, on the juice quality and sugar recovery of ratoon sugarcane clone CP-249. The study specifically assessed Brix, Pol, fiber, commercial cane sugar, and cane sugar recovery to identify an effective integrated soil and water management strategy for improving ratoon sugarcane quality and sugar recovery.

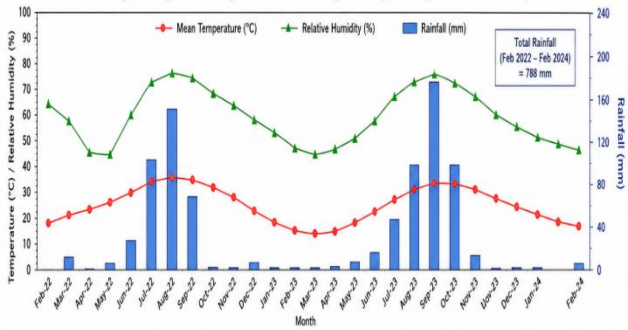
METHODOLOGY

This study was conducted at the Abdul Wali khan university, Mardan, Pakistan during two consecutive ratoon sugarcane growing seasons from February 2022 to February 2024. The objective was to evaluate the effects of integrated soil amendments and irrigation management on ratoon sugarcane juice quality and sugar recovery. The experiment was established using a Randomized Complete Block Design (RCBD) with a split-plot arrangement and three replications. Irrigation levels were assigned to the main plots, while soil amendment treatments were allocated to the subplots. Each experimental plot measured 10.4 m × 6.2 m. The ratoon sugarcane clone CP-249 was used throughout the study. Three irrigation regimes were maintained during the growing season: 100% of the recommended irrigation schedule (17 irrigations), 75% of the recommended irrigation schedule (12 irrigations), and 50% of the recommended irrigation schedule (8 irrigations). Four soil amendment treatments were evaluated, including an untreated control, press-mud applied at 3394 kg ha^{-1}, polymer-coated single super phosphate (SSP) applied at 116 kg ha^{-1}, and a combination of 50% cane trash boiler ash and 50% sulphate of potash (SOP) applied at the recommended rate. The same treatment doses were applied during both ratoon years. Standard agronomic practices for ratoon sugarcane cultivation were followed uniformly across all experimental plots to minimize variability. The ratoon crop was initiated during the second week of February in both 2022 and 2023 and harvested during the third week of February in 2023 and 2024, respectively. During the experimental period, a total rainfall of 788 mm was recorded. Weather data, including temperature, rainfall, and relative humidity, were monitored throughout the study period. At crop maturity, representative cane samples were collected from each plot, and juice was extracted using a mechanical crusher. Juice quality parameters, including Brix percentage, Pol percentage, and fiber percentage, were determined following the standard procedures described by Spencer and Meade (1955). Commercial Cane Sugar (CCS%) was calculated using the formula proposed by Chiatrakul et al. (2022), incorporating juice polarity (Pol%), total soluble solids (Brix%), and fiber content. Cane Sugar Recovery (CSR%) was subsequently estimated by multiplying CCS% by a recovery factor of 0.94.

These parameters were used to assess the influence of irrigation levels and soil amendments on sugarcane juice quality and sugar recovery efficiency.

The collected data were subjected to analysis of variance (ANOVA) using Fisher's statistical procedure to determine the significance of treatment effects and their interactions. Treatment means were compared using Tukey's Honestly Significant Difference (HSD) test at a significance level of $p \leq 0.05$. Statistical analyses were performed to evaluate the individual and combined effects of irrigation regimes and soil amendment treatments on juice quality characteristics and sugar recovery of ratoon sugarcane.

Figure 1. Agrometeorological Conditions During the Study Period (Feb 2022 – Feb 2024)



Note: Data represent monthly means of temperature (°C), relative humidity (%) and total rainfall (mm) recorded at the experimental site.

RESULTS

Effect of Irrigation Levels on Juice Quality and Sugar Recovery

The analysis of variance revealed that irrigation levels significantly ($p \leq 0.05$) affected juice quality traits and sugar recovery of ratoon sugarcane (Table 1). The highest Brix value (21.84%) was recorded under 100% recommended irrigation, which was significantly higher than those obtained under 75% (20.67%) and 50% irrigation (19.34%). A similar trend was observed for Pol percentage, where full irrigation produced the maximum value (18.73%), followed by 75% irrigation (17.61%), while the lowest value (16.42%) was recorded under 50% irrigation. Fiber percentage increased significantly with decreasing irrigation levels, with the highest fiber content (12.76%) observed under 50% irrigation and the lowest (11.24%) under full irrigation. Consequently, commercial cane sugar (CCS%) and cane sugar recovery (CSR%) were significantly improved under adequate moisture supply. The highest CCS (13.56%) and CSR (12.75%) values were obtained under 100% irrigation, whereas the lowest CCS (11.52%) and CSR (10.83%) were recorded under 50% irrigation.

Table 1. Effect of irrigation levels on juice quality and sugar recovery of ratoon sugarcane

Irrigation Level	Brix (%)	Pol (%)	Fiber (%)	CCS (%)	CSR (%)
100% Recommended Irrigation	21.84 ± 0.42a	18.73 ± 0.38a	11.24 ± 0.21c	13.56 ± 0.31a	12.75 ± 0.29a
75% Recommended Irrigation	20.67 ± 0.35b	17.61 ± 0.32b	11.89 ± 0.18b	12.71 ± 0.27b	11.95 ± 0.25b
50% Recommended Irrigation	19.34 ± 0.29c	16.42 ± 0.27c	12.76 ± 0.24a	11.52 ± 0.22c	10.83 ± 0.21c

Means followed by different letters within a column differ significantly at $p \leq 0.05$.

Effect of Soil Amendments on Juice Quality and Sugar Recovery

Significant differences were also observed among soil amendment treatments (Table 2). Press-mud application resulted in the highest Brix (22.18%) and Pol (19.11%) values, which were statistically superior to all other treatments. Polymer-coated SSP ranked second, producing Brix and Pol values of 21.36% and 18.34%, respectively. The untreated control recorded the lowest Brix (19.42%) and Pol (16.35%) values. Fiber content was significantly reduced by soil amendments, with press-mud showing the lowest fiber percentage (11.09%) compared with the control (12.68%). Similarly, CCS and CSR were markedly enhanced by amendment application. Press-mud treatment produced the highest CCS (13.94%) and CSR (13.10%), followed by polymer-coated SSP and cane trash boiler ash + SOP. The control treatment exhibited the lowest sugar recovery performance.

Table 2. Effect of soil amendments on juice quality and sugar recovery of ratoon sugarcane

Soil Amendment	Brix (%)	Pol (%)	Fiber (%)	CCS (%)	CSR (%)
Control	19.42 ± 0.31d	16.35 ± 0.28d	12.68 ± 0.25a	11.44 ± 0.24d	10.75 ± 0.22d
Press-Mud	22.18 ± 0.40a	19.11 ± 0.36a	11.09 ± 0.19d	13.94 ± 0.30a	13.10 ± 0.28a
Polymer-Coated SSP	21.36 ± 0.37b	18.34 ± 0.33b	11.53 ± 0.22c	13.28 ± 0.27b	12.48 ± 0.25b
50% Cane Trash Boiler Ash + 50% SOP	20.74 ± 0.35c	17.82 ± 0.31c	11.98 ± 0.21b	12.81 ± 0.25c	12.04 ± 0.24c

Means followed by different letters within a column differ significantly at $p \leq 0.05$.

Interaction Effect of Irrigation Levels and Soil Amendments

The interaction between irrigation regimes and soil amendments significantly influenced sugar recovery traits (Table 3). The combination of 100% recommended irrigation and press-mud application produced the highest CCS (14.89%) and CSR (14.00%), indicating a synergistic effect of adequate moisture availability and improved soil fertility. Treatments receiving polymer-coated SSP under full irrigation also showed high CCS (14.12%) and CSR (13.27%) values. In contrast, the lowest CCS (10.72%) and CSR (10.08%) were recorded in the control treatment under 50% irrigation. Although deficit irrigation reduced sugar recovery, the application of soil amendments alleviated these adverse effects, resulting in significantly higher CCS and CSR values compared with the untreated control under the same irrigation level.

Table 3. Interaction effect of irrigation levels and soil amendments on commercial cane sugar (CCS%) and cane sugar recovery (CSR%)

Irrigation Level	Soil Amendment	CCS (%)	CSR (%)
100% Irrigation	Control	12.18 ± 0.22e	11.45 ± 0.21e
100% Irrigation	Press-Mud	14.89 ± 0.35a	14.00 ± 0.33a
100% Irrigation	Polymer-Coated SSP	14.12 ± 0.29b	13.27 ± 0.27b
100% Irrigation	Boiler Ash + SOP	13.06 ± 0.24c	12.28 ± 0.23c
75% Irrigation	Control	11.42 ± 0.20f	10.73 ± 0.19f
75% Irrigation	Press-Mud	13.54 ± 0.28c	12.73 ± 0.26c
75% Irrigation	Polymer-Coated SSP	12.91 ± 0.25d	12.14 ± 0.23d
75% Irrigation	Boiler Ash + SOP	12.37 ± 0.23e	11.63 ± 0.22e
50% Irrigation	Control	10.72 ± 0.18g	10.08 ± 0.17g
50% Irrigation	Press-Mud	13.39 ± 0.26c	12.59 ± 0.24c
50% Irrigation	Polymer-Coated SSP	12.81 ± 0.23d	12.04 ± 0.21d
50% Irrigation	Boiler Ash + SOP	12.01 ± 0.21e	11.29 ± 0.20e

Means followed by different letters within a column differ significantly at $p \leq 0.05$.

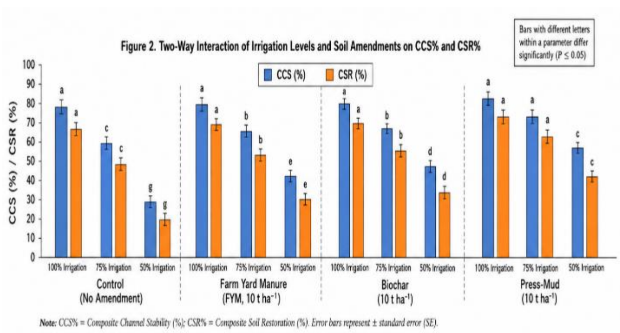


Figure 2. Two-Way Interaction of Irrigation Levels and Soil Amendments on CCS% and CSR%

Overall, the results demonstrated that both irrigation management and soil amendment application significantly enhanced ratoon sugarcane juice quality and sugar recovery. Among all treatments, press-mud combined with 100% recommended irrigation proved most effective in improving Brix, Pol, CCS, and CSR while reducing fiber content. These findings highlight the importance of integrated soil and water management practices for maximizing ratoon sugarcane productivity and processing quality.

DISCUSSION

The present study demonstrated that integrated soil and water management significantly improved ratoon sugarcane juice quality and sugar recovery. The superior performance observed under the 100% recommended irrigation regime indicates the critical role of adequate soil moisture in promoting sucrose synthesis, translocation, and accumulation in sugarcane stalks. Water availability directly influences photosynthetic activity, nutrient uptake, and assimilate partitioning, ultimately affecting juice quality parameters such as Brix and Pol percentages. The higher Brix and Pol values recorded under full irrigation are consistent with previous findings that optimal irrigation enhances sugar accumulation and improves cane quality by maintaining favorable physiological processes throughout crop development [28].

The decline in juice quality under deficit irrigation observed in the present study may be attributed to reduced photosynthetic efficiency and impaired translocation of carbohydrates from leaves to stalk tissues. Water stress often disrupts stomatal conductance, decreases carbon fixation, and limits sucrose metabolism, leading to lower sugar concentrations in cane juice [36]. Similar reductions in Brix and sucrose content under water-limited conditions have been reported in ratoon sugarcane grown in tropical and subtropical environments [12]. Furthermore, the increased fiber percentage observed under reduced irrigation levels supports the hypothesis that moisture stress promotes structural tissue development at the expense of sucrose accumulation, thereby negatively affecting sugar recovery [37].

Among the soil amendment treatments, press-mud produced the highest juice quality and sugar recovery values. Press-mud is rich in organic matter, essential nutrients, and beneficial microorganisms that improve soil physical, chemical, and biological properties. The enhanced performance of press-mud-treated plots may be associated with improved soil moisture retention, increased nutrient availability, and enhanced microbial activity, which collectively support crop growth and sugar accumulation. Previous studies have shown that press-mud application improves soil fertility and significantly increases sugarcane yield and quality parameters, particularly in ratoon crops where soil nutrient depletion is common [26].

Polymer-coated SSP also enhanced sugarcane juice quality compared with the control treatment. Controlled-release fertilizers provide a gradual supply of phosphorus throughout the growing season, minimizing nutrient losses and improving nutrient use efficiency. Adequate phosphorus nutrition promotes root development, energy transfer, and carbohydrate metabolism, thereby facilitating sucrose accumulation in sugarcane stalks. The observed improvement in Brix, Pol, CCS, and CSR values under polymer-coated SSP treatment is in agreement with reports indicating that slow-release phosphorus fertilizers enhance sugarcane productivity and processing quality [28].

The positive response of ratoon sugarcane to the application of cane trash boiler ash combined with sulphate of potash can be attributed to the contribution of potassium and other mineral nutrients. Potassium plays a vital role in enzyme activation, photosynthesis, osmotic regulation, and sugar translocation from source to sink tissues. Adequate potassium nutrition has been reported to improve sucrose accumulation and increase commercial cane sugar content [27]. Additionally, recycling sugar industry by-products such as boiler ash contributes to sustainable nutrient management and soil health improvement, supporting long-term crop productivity [2].

The significant interaction between irrigation levels and soil amendments observed in this study highlights the importance of integrated resource management strategies. Soil amendments were most effective when combined with adequate irrigation, suggesting that sufficient soil moisture enhances nutrient availability and uptake efficiency. Under water-deficit conditions, amended plots still maintained higher sugar recovery than the untreated control, indicating that soil amendments partially mitigated the adverse effects of moisture stress. Similar synergistic effects of irrigation and nutrient management on sugarcane quality have been reported by several researchers, who concluded that integrated approaches maximize nutrient utilization and improve sugar recovery efficiency [28].

Commercial Cane Sugar (CCS) and Cane Sugar Recovery (CSR) are among the most important indicators of sugarcane processing quality. The substantial increases in CCS and CSR observed under press-mud and full irrigation treatments demonstrate that improvements in Brix and Pol percentages, together with reduced fiber content, contribute directly to higher recoverable sugar. These findings are supported by previous investigations showing strong positive relationships between sucrose concentration, juice purity, and sugar recovery in ratoon sugarcane systems.

Overall, the findings suggest that integrated soil and water management is an effective strategy for enhancing ratoon sugarcane juice quality and sugar recovery. The combined application of press-mud and recommended irrigation provided the most favorable conditions for sucrose accumulation and sugar extraction. Adoption of such sustainable management practices could improve sugarcane productivity, enhance processing efficiency, and contribute to the long-term sustainability of sugarcane-based production systems [8].

CONCLUSION

The study demonstrated that integrated soil and water management substantially improved ratoon sugarcane juice quality and sugar recovery. Full irrigation (100% of the recommended schedule) produced superior Brix, Pol, CCS, and CSR values while maintaining lower fiber content than deficit irrigation regimes. Among the soil amendments, press-mud consistently provided the most favorable results, followed by polymer-coated SSP and cane-trash boiler ash combined with SOP. The interaction between irrigation and soil amendments further indicated that adequate water availability enhanced the effectiveness of nutrient management practices. The combination of 100% recommended irrigation with press-mud resulted in the highest sugar recovery and overall juice quality. Therefore, integrated application of appropriate irrigation and soil amendments, particularly press-mud, can be recommended for improving the quality and sugar recovery of ratoon sugarcane.

Ethical Approval

Not applicable. This study did not involve human participants, animals, or identifiable personal data.

Informed Consent

Not applicable, as this study did not involve human participants or direct data collection from individuals.

Data Availability Statement

The data generated and analyzed during this study are included in the article. Additional information is available from the corresponding author upon reasonable request.

Author Contributions

Aqila Azam, Ayesha Hidayat, Samreen, and Wasim Khan contributed to the conceptualization, methodology, data collection, analysis, manuscript writing, review and editing, and final approval of the manuscript.

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Conflict of Interest

The authors declare that they have no competing interests.

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Use of Artificial Intelligence

Grammarly was used solely for grammar, spelling, punctuation, and language correction. No generative AI was used to create, interpret, or modify the scientific content of the manuscript. The authors remain fully responsible for the accuracy, originality, and integrity of the work.

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