Importance of water management in sugarcane farming, including irrigation techniques, water-use efficiency, and the challenges posed by water scarcity

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Abstract: Efficient water organizaction is crucial for ensuring the long-term viability and efficiency of sugarcane cultivation, considering the crop's substantial water needs. This article analyses the essential water management components in sugarcane farming, specifically emphasizing improved irrigation methods, water-use efficiency, and increasing difficulties caused by water scarcity. Given the significant water requirement of sugarcane, farmers must adopt effective irrigation techniques like drip and sprinkler systems. These methods enhance water-use efficiency by providing accurate quantities of water directly to the root zone, reducing losses from evaporation and runoff. Optimizing water utilization is crucial to improving harvests and preserving soil health, directly impacting sugarcane production's quantity and profitability. The escalating difficulties of water shortages, especially at the areas where water incomes are diminishing as an outcome of variables such as climate change, population expansion, and conflicting demands from other sectors. These difficulties emphasize the significance of implementing sustainable water management strategies to mitigate the hazards linked to water scarcity. An investigation is conducted into the utilization of technologies such as soil moisture sensors, automated irrigation systems, and water recycling to enhance the durability of sugarcane cultivation. This article highlights the importance of addressing these critical concerns and emphasizes the necessity of adopting a comprehensive strategy for water management. These techniques are essential for confirming sugarcane agriculture's long-term sustainability and environmental well-being, particularly in light of increasing water scarcity.

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Introduction

Sugarcane, scientifically known as *Saccharum officinarum* L., is a long-established source of energy for humans and has more recently been employed as an alternative to fossil fuels in automobiles. Sugarcane cultivation is limited to countries situated within the latitudes of 36oN and 31oS, encompassing both tropical and subtropical areas. Sugarcane is grown in 107 countries worldwide. The land measures 20.41 million hectares and produces a whole of 1332 million tonnes (Tayade et al. 2020). There is considerable disparity in both the magnitude of sugarcane plants and the quantity of sugarcane yielded among other countries. Brazil possesses the greatest expanse of land, at 5.34 million hectares, whereas Australia exhibits superior productivity, achieving a yield of 85.1 tons per hectare. India, Brazil, Pakistan, and China remain the primary growers, jointly accounting for over 50% of worldwide (Adetoro et al. 2020). Sugarcane ranks as the second most important crop in Pakistan, covering an area of 0.978 million hectares and constituting about 3.7% of the nation’s Gross Domestic Product (Farooq et al. 2019).

Sugar cane currently accounts for 4.9% of the total cultivated acreage and contributes 11% to the overall value of all crops (Dingre 2023). The sugar business plays a crucial role in our nation's economy. Sugarcane provides not only sugar but also ethanol, fiber, organic fertilizer, and various other byproducts/co-products that help with ecological sustainability. Molasses is the most cost-effective rare substantial stills. Bagasse is acknowledged as a viable alternative to timber as a primary substantial in paper and pulp manufacturing (Cardozo et al. 2018). The sector employs a workforce of more than one million workers, consisting of management specialists, technicians, engineers, and financial experts, as well as professional and unskilled laborers (Minhas et al. 2020). Honey manufacturing plays a substantial role in the rural budget as a result of the strategic location of mills in rural areas (He et al. 2021). The increasing amounts of anthropogenic greenhouse gases (GHGs) are directly linked to specific external elements that contribute to climate change and are accountable for the observed variations in climate-related phenomena, such as heightened severity of precipitation, typhoons, overflows, and lacks (Vasantha et al. 2020). The rise in worldwide temperature is predominantly attributed to the combustion of vestige material (Tayade et al. 2023).

Farming accounts for roughly 15% of anthropogenetic greenhouse gas (GHG) releases globally, with the extra 16% attributed to disforestation and land alteration for agrarian use (Popin et al. 2020). Furthermore, agriculture is directly affected by these effects, resulting in anticipated consequences. Increased risks for provincial and worldwide food security (Dattamudi et al. 2019). The terrestrial use variation and forestry sectors have been the main drivers and largest net greenhouse gas (GHG) emissions in Brazil during the previous decade. More precisely, these emissions are mostly associated with the transformation of forests and plants in corridors into agricultural activities (Lefebvre et al. 2021). Based on a recent analysis conducted by the Brazilian government, there was a significant reduction of 85% in greenhouse gas release from activities about land-use alteration, and forestry (LULUCF) sector (Bordonal et al. 2018) The decrease in desertification in the Amazon region is the main reason for this trend (Cabral et al. 2020). Therefore, a documented reduction in deforestation led to a 41% decrease in the whole countrywide releases, precisely from 2042 to 1202 Tg, CO_2. (Yang et al. 2021). Brazil has played a crucial role in the worldwide advancement and utilization of bioethanol, a viable alteration that can effectively decrease GHG production by substituting fossil fuels. Research has indicated that the utilization of bioethanol can result in a decrease in GHG releasing as much as 85% (Vasconcelos et al. 2022).

The global production of bioethanol, a commonly used biofuel, reached 96 billion liters Tyagi et al. 2019). Brazil, responsible for 28% of worldwide ethanol production, ranks as the world's second-largest producer of ethanol in the United States, which is responsible for 59% of worldwide output. (Antunes et al. 2019). Therefore, Brazil plays a pivotal role in meeting the current and future global demand for ethanol (Karp et al. 2021). Various nutritional crops suitable for biofuel production include cereals such as maize, sorghum, and wheat; sugar crops like sugarcane and sugar beets; and starch crops such as cassava, soybean, and oil palm. According to Figure 1, Brazil is the leading global producer of sugarcane. In the 2016/17 year, the country had a cultivated area of 9.2 million hectares, mostly located in the south-central zone, according to 90% of the total area (Mączyńska et al. 2019). The Brazilian Alcohol Program (palcohol) was initiated in 1975 to diminish dependence on oil imports by promoting the manufacturing of ethanol generated from sugarcane. However, the positive effects on the environment became clear when it was shown that there was a reduction of 27.5 grams of CO_2 equivalent emissions as a result of partially replacing petrol with an alternative fuel in Brazil (Dibazar et al. 2023).

Furthermore, the Brazilian government has declared aggressive objectives in the recent Paris Agreement inside the United Nations Framework Convention on Climate Change. The goals involve achieving a reduction in greenhouse gas emanations of 43% below current levels documented in 2005 to the year 2030 (Martinez et al. 2018). The government of Brazil has established the "RenovaBio" initiative, along with other strategies to accomplish this objective. The objective of this initiative is to enhance the percentage of renewable fuels in the nation's energy composition (Niju et al. 2020). Consequently, it is projected that ethanol output will increase from 28 billion liters annually. The projected increase in the volume of liquid consumption is expected to reach approximately 50 billion liters by 2030, according to the MME 2017 report. Although sugarcane has many benefits as a renewable source for producing biofuels, there is increasing concern about its possible negative impact on the environment (De Almeida et al. 2023). These factors encompass the proliferation of sugarcane farming and the consequent alterations in land utilization, which have the potential to disrupt the availability of food. Furthermore, there are apprehensions regarding the release of greenhouse gases from agronomic efforts and agricultural activities, unnecessary water consumption resulting in eutrophication, depletion of soil biodiversity, and faster soil erosion (López et al. 2021). Furthermore, the extent to which biofuels can decrease greenhouse gas (GHG) emissions outcome varies depending on the particular techniques used to utilize feedstocks and corresponding farming practices (Vandenberghe et al. 2022).

An analysis of the energy balance and greenhouse gas (GHG) emissions of various biofuel options has recently caused a major disagreement and raised concerns about their authentication (Uppalapati et al. 2024). Hence, the ongoing advancement in science and technology is crucial to guarantee the enduring viability of sugarcane ethanol, particularly concerning the sugarcane farming industry (Pereira et al. 2019). The industry mentioned is accountable for 81–90% of the total greenhouse gas emissions produced throughout the process of production of ethanol in Brazil (Seabra 2011). One concern related to the growing worldwide production of biofuels is the requirement for more land fulfill the future requirement of ethanol (da Silva Neto et al. 2020). Goldemberg (2014) anticipates that global ethanol production derived from maize and sugarcane volume is projected to rise from 80 billion liters to more than 200 billion liters by 2021 (Batlle et al. 2021). To achieve ecologically sustainable ethanol production, it is necessary to evaluate many components of the production process. The factors to consider are land use change, the trade-off between food security and ethanol production, agricultural management methods, water quality and availability, energy balance, and carbon footprint (Mbothu et al. 2019). Within this specific context, the growing of sugarcane offers considerable potential to provide environmental benefits by enhancing the agronomic invention process (Elshout et al. 2022).

It involves the incorporation of sugarcane into food production, increasing the use of pastoral land, minimizing the difference between anticipated and achieved yields, enhancing nitrogen utilization efficiency, preventing the burning of leftover material, and adopting no-till or reduced tillage methods (Singh et al. 2019). These measures collectively aid in reducing the local ecological influences of sugar cane farming. This essay aims to analyze the notable sustainability problem related to the ecological significance of the quickly increasing sugar cane business in Brazil, particularly in the agricultural sector (Hernandes et al. 2018). The primary objective is to ascertain the deficiencies in knowledge and establish the prioritization of upcoming investigation endeavors. Then, the study aims to gather and summarize the present information regarding the impacts of sugar cane growth on changes in terrestrial use and its struggle with nutrition manufacture, as well as possible occasions aimed at agronomic increases Bahati et al. 2022). The study also examines current advancements in the conservational impact of sugar cane harvesting and proposes prospects to enhance Brazil's sugarcane production system and improve its productivity (Canisares et al. 2020).

The productivity of biofuels is a matter of concern because it involves the replacement of nutrition and fodder yields with sugar cane and the clearing of forests for biofuel production (Shelar et al. 2023). The effects of biofuel production on biodiversity, food costs, and greenhouse gas emissions resulting from changes in land use can differ according to the specific methods used (Ramírez-Contreras et al. 2021). The potential decrease in carbon emissions (C) achieved by the utilization of biofuels can be nullified by the adverse consequences of extending sugarcane plantations into natural forests or grasslands (Naseri et al. 2021). During their evaluation of the direct land-dwelling modification (LUC) to sugar cane plantations in southcentral Brazil (Hiloidhari et al. 2021). The analysis revealed that almost 96% of the recent growth took place on pastures (69.7%), annual crops such as soybean, corn, sorghum, and cotton (25%), and citrus (1.3%) (Nogueira et al. 2024).

The present information demonstrates that the cultivation of sugarcane led to a substantial decrease in pastures. However, it did not have a direct influence on the process of deforestation in the agricultural area where the majority of the expansion took place (Wadghane et al. 2023). Currently, evaluations of the effects of changes in land use on the balance of carbon in the soil also consider the reduction in carbon dioxide emissions achieved by growing sugarcane. In their study, Mello determined that the amount of carbon lost from the soil was 21 and 5.7 megagrams of carbon per hectare when native vegetation and pastures were converted to sugarcane, respectively, during 20 years (Vera et al. 2018). Based on the ethanol C offset of 2.7 Mg C ha−1 year−1, as proposed by Fargione (2008), it would require roughly 8 years to compensate for the soil C deficits caused by land use change (LUC) from native plants. When it comes to land use change (LUC) from pastures, it would require 2-3 years to offset the soil carbon (C) deficits. Nevertheless, the maximum of the sugarcane ranges examined in this research whichever subjected to burning methods during harvesting or had recently discontinued this practice during the past 3 years before the soil samples were collected (Naresh et al. 2021). This increase occurs at a rate of 0.16 megagrams of carbon per hectare per year. Furthermore, the sugarcane biomass has an annual carbon storage rate of 15.9 megagrams per hectare (Gunarathna et al. 2018). Therefore, if we replace ecosystems that have low carbon stocks, such as tarnished grasslands, with high-yielding energy crops like sugarcane or oil palm, it has the potential to reduce or eliminate the time needed to settle the carbon debts that emerge from changing how the land is used (Kumar et al. 2024).

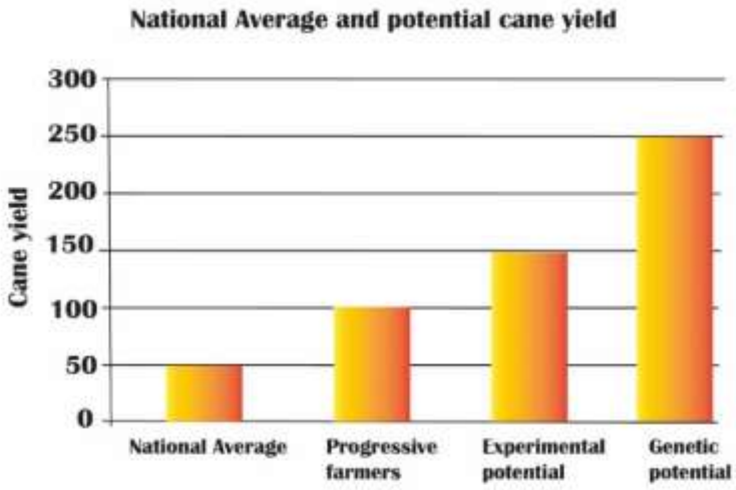


Figure (a)

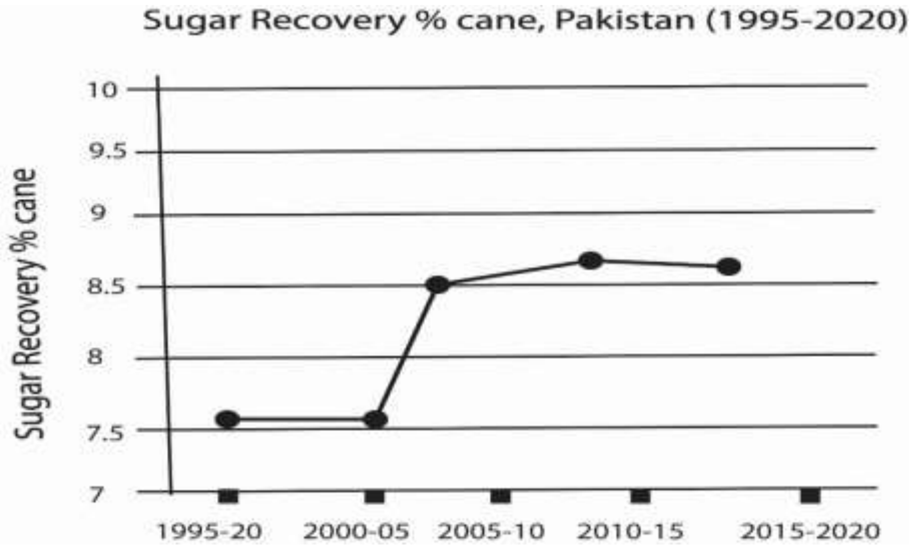


Figure (b)

Figure 1. Ecological determinants of sugarcane cultivation

Table 1. **Pakistan's cane yield and production**

Years	Region *000* ha	Manufacturing *000* tons	Cane Productivity M. t ha^{-1}
2015-2020	1021	47898	46.8
2010-2015	928	40884	43.8
2005-2010	897	33578	37.4
2000-2005	609	21649	35.8
1995-2000	465	15847	33.8
1990-1995	244	7191	29.1

Table 2. **Cane crushed, cane produced and percentage of utilization (2005-1995)**

Annual	2004-05	2001-01	1999-00	1996-97	1995-96
Area (000 ha)	923.2	961	1009.9	964.4	966.5
Sugarcane production (000 tons)	43532	43591	42001	41998.5	45229.6
Installed capacity (000 tons)	64651	56251	55801	54752	54301
Cane utilized by mills (000 tons)	281512	27351	28981	29409	32102
% age of utilization	73.73	67.46	69.01	65.12	73.74 62.23

(Dhanapal et al. 2019).

Efficiency of photosynthesis

Sugarcane is highly proficient at photosynthesis. A C4 plant efficiently changes about 2% of the incoming astrophysical energy in the biomass. With a photosynthetic rate of 12-14 µ µmol CO2/m2/sec, this crop plant surpasses all others in its ability to convert solar radiation and carbon dioxide from the midair into diet, fuel, and fiber (Francis et al. 2020).

Climate

Sugarcane farming necessitates a climate that is either humid or semitropical, with the lowest annual rainfall of 599 mm. Sugarcane is grown in three distinct ecological zones in Pakistan: the northwestern, dominant, and southwestern areas. Pakistan's climate is predominantly described as subtropical arid to semiarid. The temperature fluctuates between an average minimum of 4oC in January and December and a maximum of 38oC in June and July. In certain limited areas, the low temperatures during wintertime occasionally hinder or halt the growth of sugarcane. The climate consistently supports crop productivity throughout the year. However, the low amount of rainfall caused by adverse weather conditions is a significant obstacle to sugarcane crop development in Pakistan (Mehdi et al. 2024)

Measurement of area, efficiency, and usage

Despite extensive energy, production of sugarcane in the country remains much lower compared to the majority of sugar-producing countries worldwide. The main factors contributing to low production are improper plant population, inadequate cultivation methods, insufficient nutrition management, inadequate irrigation water supply, and insufficient plant protection techniques. These issues require rapid attention (Ouko et al. 2022). Over the past 50 years, the area dedicated to growing sugarcane has grown by 310%, while production has climbed by 566%. The yield of sugarcane has also improved by 200% (Ali et al. 2021). Additionally, the national average for sugar recovery has increased from 7.50 to 8.70. The manufacturers' consumption of sugar cane through periods of poor production varied from 62% to 68%. Assuming that there will be 81% consumption in the upcoming devastating periods is nothing more than hopeful and thoughtful. The shift to gurh-making has consistently been more appealing during periods of limited sugarcane availability (Chen et al. 2023).

The total production of sugarcane was 43.5 million tons, which fell short of the installed capacity of 78 sugar mills, which was 64.65 million ns. Hence, to operate the facilities at their current installed capacity, an additional 22.2 million tons of yield-making will be necessary. When new workshops are established or existing units are expanded, they need to be aware that they must make extra efforts to increase cane output to meet the demands of the increased capacity (Carrer et al. 2022).

Water Use Efficiency of Irrigation (IWUE)

The maximum efficiency of water used in the irrigation was 1942 kilogram/ha cm was seen in furrows that were 75 meters in length, as shown in Table 4. Out of various release rates and decreased height strictures, the release of water at a rate of 10 liters per second with a cut-off length of 85 meters resulted in the maximum irrigation water use efficiency (IWUE) of 2239.71 kilograms per hectare intimate (Dhanapal et al. 2019). The conservative technique of irrigation resulted in significantly poor irrigation water use efficiency (IWUE). The reduction in water availability resulted in a decrease in cane yield due to the restriction of yield-contributing characteristics (Rana et al. 2023). The utilization of 10 low-pressure sprinklers with an 85-cut-off length has resulted in a 41% reduction in overall irrigation water consumption compared to the conventional border irrigation approach commonly used by farmers. An inverse association was established between water stress and reduction (Anjaly et al. 2024).

Leite et al. (2020) observed a significant decrease in the height of the cane and the average length of internodes. It was proposed that water stress had a substantial impact on the elongation of cells. Soil has a significant role in determining the total water need and water retention capacity. Due to its economic importance as a vegetative growth-based crop, there exists a direct correlation between the growth rate of sugarcane and the availability of soil moisture (Venkatesh et al. 2022). In their study, Mathew and Varughese determined that furrow irrigation significantly enhanced the accessibility of soil moisture. Increased furrow length. The differences in nutrient absorption appear to be influenced by the variations in dry matter production across different treatments (Mele, A. 2019). Among the various discharge rates and cut-off lengths, the treatment that involved irrigating the field at a rate of 10 liters per second with a cut-off length of 85 meters showed the highest uptake of nitrogen (98.35 kg/ha), phosphorus (23.40 kg/ha), and potassium (121.28 kg/ha), and this change was starting to be statistically important (Adib et al. 2022).

The increase in nutritional absorption seen throughout the treatment may be attributed to the substantial formation of dry matter, along with high efficiencies in nutrient and water utilization. The cultivation of sugarcane, which yields a large volume of crop, depletes a significant quantity of nutrients (Nur et al. 2020). According to Mukerji and Verma (1950), a crop of 76 tonnes of cane stalk per hectare, including leaves and tops, typically removes 117 kg of nitrogen (N), 72 kg of phosphorus (P2O5), and 353 kg of potassium (K2O) per hectare, as well as other significant amounts of micronutrients from the soil (Struik et al. 2022).

Table-3. Nutrient uptake and efficiency of water use irrigation in relation to various water managing strategies

Treatment	**IWUE (kg/ha cm)**	**NPK uptake (kg/ha) by sugarcane**					
		Nitrogen (N)		Phosphorous (P)		Potassium (K)	
		Content (%)	Uptake kg/ha	Content (%)	Uptake kg/ha	Content (%)	Uptake kg/ha
Furrow length (m)-F	-	-	-	-	-	-	-
F_1 -50	1668.01	1.42	71.60	1.07	15.25	1.52	87.81
F_2-75	1941.48	1.42	77.56	1.11	18.61	1.52	107.01
C D (P=0.05	22.25	-	4.33	-	3.32	-	10.26
Discharge(lps)+cut off Lenth (m)-D	-	-	-	-	-	-	-
D_1 (8+75)	1955.92	1.40	68.98	1.11	15.25	1.52	88.66
D_2 (10+75)	2220.30	1.41	72.15	1.08	15.15	1.50	89.04
D_3 (8+85)	1728.88	1.42	73.13	1.11	16.65	1.52	95.63
D_4 (B+75)	2239.70	0.41	97.34	0.11	22.42	0.52	120.29
D_5 (B+85)	1355.45	0.41	65.5	1.07	12.36	1.54	88.92
D_6 (	1301.27	0.41	68.24	0.08	15.63	0.52	91.70
CD (P=0.056)	19.49	-	4.81	-	3.71	-	10.36

Historically, the majority of sugarcane farming systems employed surface irrigation, particularly furrow irrigation, due to its uncomplicated nature and cost-effectiveness. However, the rising expenses associated with electricity and labor, as well as the growing need for limited water supplies, have resulted in a higher prevalence above or drip irrigation techniques. Nevertheless, channel irrigation remains the predominant technique employed globally (El-Hendawy et al. 2024). Furrow irrigation is not popular among sugarcane farmers due to its major limitations, which include the high labor required and low water use efficiency (WUE) caused by filtration and tailwater sufferers (Al-Salman 2021). Channel technique exhibits much lower efficiency on soils with a light texture compared to overhead and drip irrigation systems. Despite the implementation of techniques such as low movement rates (Shinde 2007), flow irrigation (Pires 2012), and local modifications (Mahesh 2016), the efficiency of furrow irrigation has not reached satisfactory levels, and the labor requirement remains high. To irrigate the sugarcane crops, hydraulic burden is used in the sprayer and drip irrigation processes. In key areas like the development of plant growth and aquatic conservation, shallow and sub-shallow drip irrigation systems outperformed surface irrigation systems in the study comparing external drip irrigation, shallow irrigation, and sub-shallow drip irrigation for sugarcane (Kaushal 2012).

When subsurface drip irrigation is used instead of rainfed farming. (Gunarathna et al. 2018) found that fresh cane production has increased. Both drip irrigation and rain gun sprinkler irrigation produced sugarcane yields that were comparable to or higher than those obtained with surface watering, according to research by (Ranomahera et al. 2020). Fall gun sprayer irrigation used 32% less water than irrigation through the drip method, although the latter offered a more even dispersion of water. 22. (Gulati et al. 2018) compared dissimilar tap pressures (4.1, 4.6, and 5.1 bars) and spout diameters (3.3 mm × 5.3 mm and 4.3 mm × 5.7 mm) in a plantation, she found significant bottomless filtration decreases (approximately 41%) with sprayer technique in Brazil. This activity results in greater production costs and detrimental consequences on the environment since it uses sources of water, energy, and resolvable nutrients inefficiently (Sachin et al. 2024). By precisely supplying the exit amount of water and ensuring that the root area receives enough oxygen, subsurface drip irrigation promotes plant development and productivity. Furthermore, by lowering losses from denitrification, deep percolation, and runoff—all possible problems with other techniques—it improves the effectiveness of applied fertilizers (Dias et al. 2018).

Depending on variables including earth kind, soil depth, and crop variety, the optimal depth for subsurface drip lines varies from 11 to 81 cm. This is because capillary action promotes upward water circulation, which aids in water absorption. When the same amount of water is used for both shallow and subsurface drip irrigation, the Former covers an area that is about 50% larger (Minhas et al. 2020). According to Mahesh sub shallow and surface drip irrigation can cut water use compared to surface watering by 31% and 23%, respectively. Additionally, compared to surface irrigation with a conventional fertilizer application, the researchers discovered that subsurface fertigation produced noticeably higher sugarcane productivity and water usage efficiency (Sanghera 2021). However, there are several drawbacks to subsurface drip irrigation, such as impaired germination because of insufficient capillary movement, problems with salt, obstruction of the nozzle, and uneven water distribution (Mortel et al. 2023). Furthermore, because accurate design and a skilled operator are required, it is not always guaranteed to attain maximum productivity and performance (Barbosa et al. 2024).

Therefore, it is essential to suggest new methods or strategies for subsurface irrigation systems to achieve improved accuracy, all the while addressing the inherent shortcomings of current subsurface irrigation technologies. The Japanese prefecture of Okinawa is made up of several tiny islands with little surface water resources. Because of this, water-efficient irrigation methods are required for sugarcane agriculture in this area (Watanabe et al. 2020).

However, drip irrigation is not extensively used by sugarcane growers in the prefecture despite its high water efficiency since it is a demanding task that demands constant supervision, and many elderly farmers prefer farming methods tless effort (Van Antwerpen et al. 2022). Hence, to enhance the sustainability and economic feasibility of the sugarcane farming system in Okinawa, it is imperative to employ water-efficient irrigation methods that demand minimal supervision. The utilization of an optimized subsurface irrigation system (OPSIS) is a novel approach for irrigation upload crops. The capillarity process is responsible for supplying water to the root zone (Bispo et al. 2022).

The main water management system of OPSIS consists of a solar-powered submersible pump, a water tank, a water supply column, and a fertilizer tank. The water distribution system consists of a water distribution column located at the beginning of the field, perforated pipes buried parallel to the surface of the field irrigation, and PVC or metal sheeting to regulate seepage losses. The ability of OPSIS to lower surface runoff and evaporation sets it apart from other subsurface irrigation systems (Wakasugi 2017). Furthermore, it is an efficient way to reduce percolation losses, which are a common problem with underground irrigation alternatives (Wakasugi 2017). With just a few operational actions and a modest solar-powered pump to raise water and create pressure, OPSIS has the potential to drastically lower operating costs for Okinawan sugarcane growers (Wakasugi 2017). Solar radiation drives a solar-powered pump in OPSIS, which starts the flow of water. There is no need for human involvement in this process; everything happens automatically. But the irrigation, which uses perforated pipes to release water, is based on the moisture content of the soil surrounding the pipe and the inside of the pipe.

Furthermore, according to Wakashugi (2017), it can remain in place during a variety of field procedures, with mechanical harvesting. OPSIS is in line with Okinawan sugarcane producers' low intervention requirements. Furthermore, if farmers irrigate their crops by a set timetable and quantity, any sudden downpour following the irrigation may lead to a wasteful consumption of water. On the other hand, the OPSIS irrigation system irrigates the crops only as needed. However, because there isn't much thorough information regarding OPSIS, it's still relatively unknown in Okinawa. The comparison of OPSIS with other irrigation technologies must therefore consider both yield and efficient water usage is crucial in small islands with limited water supplies, as it directly impacts both performance and water conservation. Consequently, we carried out cultivation experiments in Okinawa to analyze the disparities between typical spray irrigation systems and OPSIS in terms of growth and production parameters, water usage, and other aspects (Gunarathna 2018).

2.2. Installation of irrigation system

The OPSIS treatments involved the creation of two land areas of 6.4 m × 49 m. This was achieved through positioning five OPSIS lines with a spacing of 1.2 m. Previously, the main water management system was recognized (Coelho et al. 2019). The irrigation system was supplied with nutrients from a self-regulating fertilizer reservoir. The water distribution column, responsible for delivering water to five irrigation supply lines, was first placed in a vertical position at the start of the field. The irrigation lines were installed at a depth of 45 cm below the soil surface. A trapezoidal cross-section was created by positioning the seepage barrier beneath the supply line (Ravikumar et al. 2021). The trapezium's dimensions were as follows: a height of 15 cm, a top width of 30 cm, and a bottom width of 12 cm. Throughout the agricultural growing season in OPSIS treatments, irrigation was automatically initiated and discontinued in October, coinciding with the crop harvest (Sheini-Dashtgol et al. 2020). Two plots measuring 16.9 meters by 50 meters were set up for the sprinkler irrigation treatments. This was accomplished by installing impact-type sprinklers that are readily available for purchase. The implementation of irrigation involved the use of a fixed-interval irrigation plan, which is comparable to the predominant technique employed in Okinawa (Powell et al. 2019).

2.3. Sampling of plant growth and yield

The non-destructive sampling technique was employed to measure the plant height and cane diameter of the main crop and first ratoon crop, which were cultivated throughout the summer and spring seasons, respectively. These plants were selected randomly from the central three rows of each plot (Yu et al. 2020). The study utilized linear mixed-effects analysis, specifically employing the lme4 package of R statistical software (R Foundation for Statistical Computing, Vienna, Austria). The purpose was to evaluate the influence of the irrigation method on the variables of height and diameter. The analysis used a linear mixed-effect model, with the irrigation method as the fixed effect and the crop type (main crop or ratoon) as the random variable (Pirhadi et al. 2018). There was a lack of engagement. The normality of errors was evaluated by visually inspecting residual plots. The study employed likelihood ratio tests to compare the means of different groups. The complete models, which included the influence of irrigation, were compared to the null models, which did not consider the effect of irrigation (Armanhi et al. 2018). To assess yield, a random area of 5.2 m2 was selected in each plot during the harvest of the main crops planted in spring and summer, as well as the two subsequent crops. Baddeley published this approach in (Flack-Prain et al. 2021).

The weight of recently harvested cane was measured using a top-loading balance. The vernier caliper was used to measure the average diameter of the harvested cane, while the measuring tape was used to measure the average length of the cane acceptable for milling (Sanches et al. 2019). The sugar content of the cane juice taken from the middle internode was measured using a portable refractometer, which provided the Brix value. The recorded measurements were calibrated to a temperature of 20 ◦C. The yield survey also involved the enumeration of the number of stalks that are appropriate for grinding (Najarian et al. 2020).

2.4. Quantification of Irrigation Water Consumption

A survey was conducted to assess the amount of water used for irrigation in the first and subsequent crops using sprinkler irrigation and OPSIS techniques during the growing regrowth commend and persisted (Bahmani et al. 2018). The irrigation of the second ratoon crop commenced in February and persisted until October. The quantity of irrigation employed in the OPSIS treatment was quantified by the utilization of water level monitors affixed to the primary water reservoir. The water level was measured at regular hourly intervals and then converted into the daily amount of water needed for irrigation (Chukalla et al. 2021).

2.5. Water Use Efficiency

The purpose of effective rainfall, which pertains to the amount of rainfall that plants can efficiently utilize, was conducted following the methods described by Brouwer and Heirloom. The determination of total and irrigation water consumption efficiencies was conducted by applying Equations (1) and (2) as outlined by (Marcos et al. 2018).

$$\text{Efficiency of water supply} = \frac{\text{Yield of cane (t/ha)}}{\text{Average water used (cm)}}$$

$$\text{Efficiency of Irrigation Water supply} = \frac{\text{Yield of cane (t/ha)}}{\text{Average water used (cm)}}$$

1.2. Absent component of drip irrigation

Around 81% of the worldwide irrigated areas make use of flood/surface irrigation systems. These systems generally have a field-level application efficiency that falls between 30% and 52% (Bhatt 2020). Conversely, drip irrigation exhibits a high level of irrigation efficiency, ranging from 70% to 90%, as it effectively reduces both surface runoff and deep percolation losses (Chand et al. 2021). Conventional drip irrigation (CDI) was first implemented in India for commercial purposes in the early 1970s. Its usage has experienced substantial growth in recent years, primarily because of the financial support offered by the central and state governments in the form of subsidies. From 1985 to the present, the amount of land in India utilizing drip irrigation has increased significantly, expanding from a mere 1500 ha to a substantial 1.9 million ha. According to the International Commission on Irrigation and Drainage (ICID 2015), India has now become the leading country in terms of land area utilizing drip irrigation, surpassing the United States. These subsidies have been provided as part of several initiatives to encourage the implementation of microirrigation. Tamil Nadu's micro irrigation area is considerably lower (0.15 million hectares) in comparison to other Indian states such as Maharashtra, Karnataka, Gujarat, and Andhra Pradesh. Thus, there is a notable potential to enhance the extent of micro irrigation in the state (Marimuthu et al. 2024).

Despite considerable progress and recognition of drip technology, its application has mostly been concentrated in regions with extreme water scarcity and on high-value crops such as perennial and horticultural crops (Idiris Adam 2018). The main considerations for farmers to adopt drip irrigation are water scarcity and profitability. Although there are other reasons for the limited adoption of drip irrigation, it has been noted that the advantages, as explained by extension workers, mostly emphasize water conservation rather than improving yield (Farhate et al. 2019). Farmers in states like Tamil Nadu, where groundwater irrigation is prevalent, have little incentive to adopt costly technology unless it becomes necessary. This is due to the availability of low-cost or free water from public irrigation systems or well irrigation, as well as the provision of free or subsidized electricity. (Momii et al. 2021). Hence, the focus on advocating for drip irrigation systems should be shifted towards improving productivity by minimizing water and fertilizer usage, cutting down on labor expenses, and maximizing revenues through accurate water and nutrient management. Impoverished farmers in developing nations do not have the money to acquire drip irrigation systems (Gonçalves et al. 2022).

These strategies are not suitable for disadvantaged farmers with limited land holdings who also need access to irrigation water. The main obstacles hindering the expansion of CDI are the substantial initial costs, often ranging from US $1500 to US $2500 per acre, and the scarcity of knowledge in constructing drip systems. Most of the drip irrigation companies approved by the Indian government do not provide a method that is appropriate for plots of land measuring 0.4 hectares.

Nevertheless, in reality, the typical small-scale farmer in India may own 3 to 4 smaller non-adjacent parcels of land, each measuring between 0.1 and 0.2 hectares (Wondatir and Belay 2020)

2.1.2. Irrigation techniques

In sugar cane farming, efficient irrigation techniques play a crucial role in ensuring high yields and optimal crop growth. In Pakistan, where sugar cane is a major cash crop, farmers employ various irrigation methods to cater to the crop's water requirements. Some common techniques used include flood irrigation and furrow irrigation. Additionally, more modern and water-conserving methods like drip irrigation and sprinkler irrigation are also being adopted, which help reduce water waste and promote precise water application. These techniques not only help in reducing water scarcity but also contribute to increased sugarcane productivity and better crop quality.

2.1.2.1. Conventional drip irrigation-CDI

The CDI (Crop Drip Irrigation) system of Netafim Company utilizes pressure-compensating drippers with a flow rate of 2 liters per hour. These drippers are installed in a 16 mm OD lateral pipe with a spacing of 50 cm between each dripper (known as inline drippers). The experimental plot consists of two different spacing treatments: paired row spacing of 0.75 m × 1.35 m and single row spacing of 1.50 m (Sivarasan et al. 2022). Paired row planting involves planting two rows of sugarcane with a spacing of 0.75 m, leaving a space of 1.35 m between the rows. This results in a lateral-to-lateral spacing of 2.10 m. Drip providers mostly endorse this strategy to minimize the expense of drip laterals. The arrangement is depicted in detail in Figure 1, while Figure 2 shows the site map (Marimuthu et al. 2024).

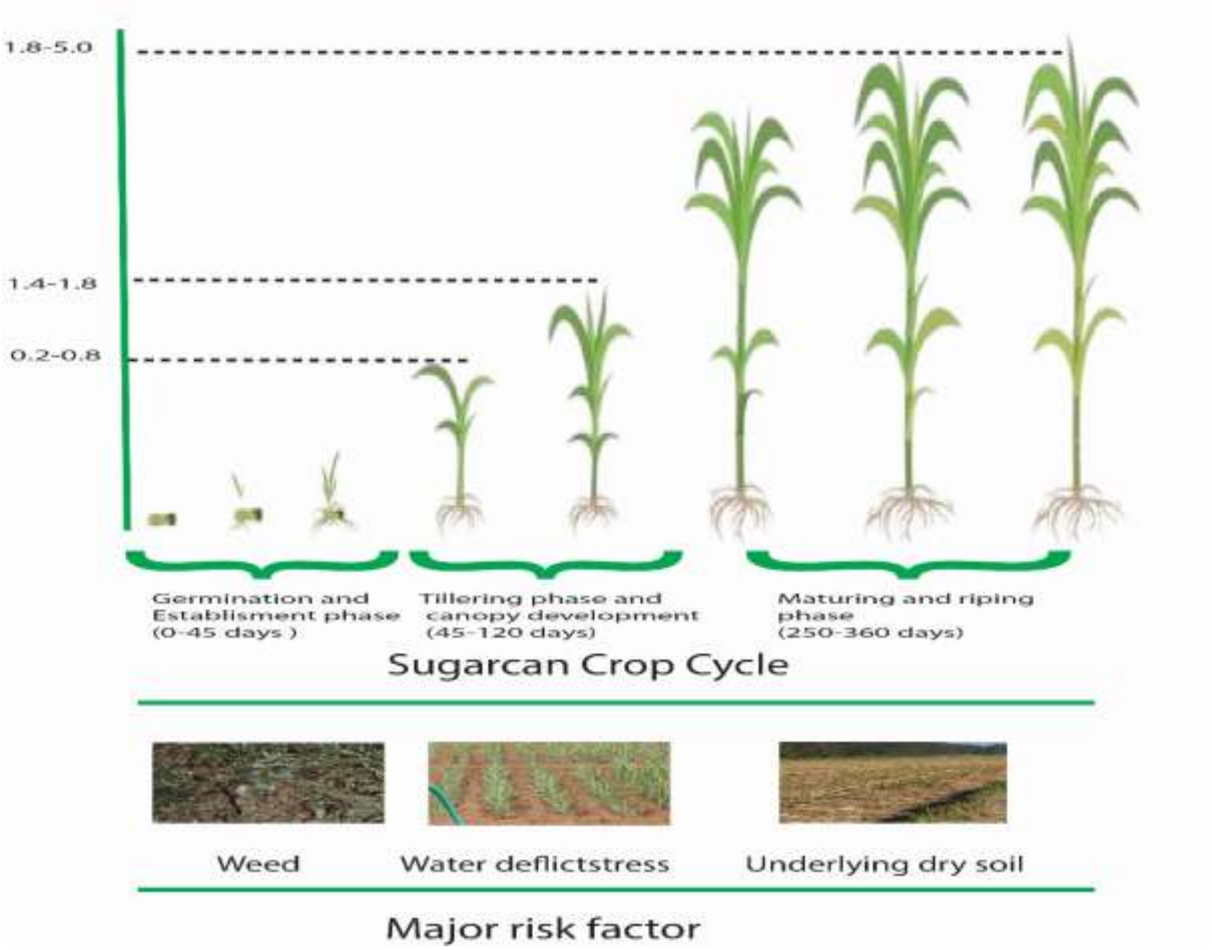


Fig (1)

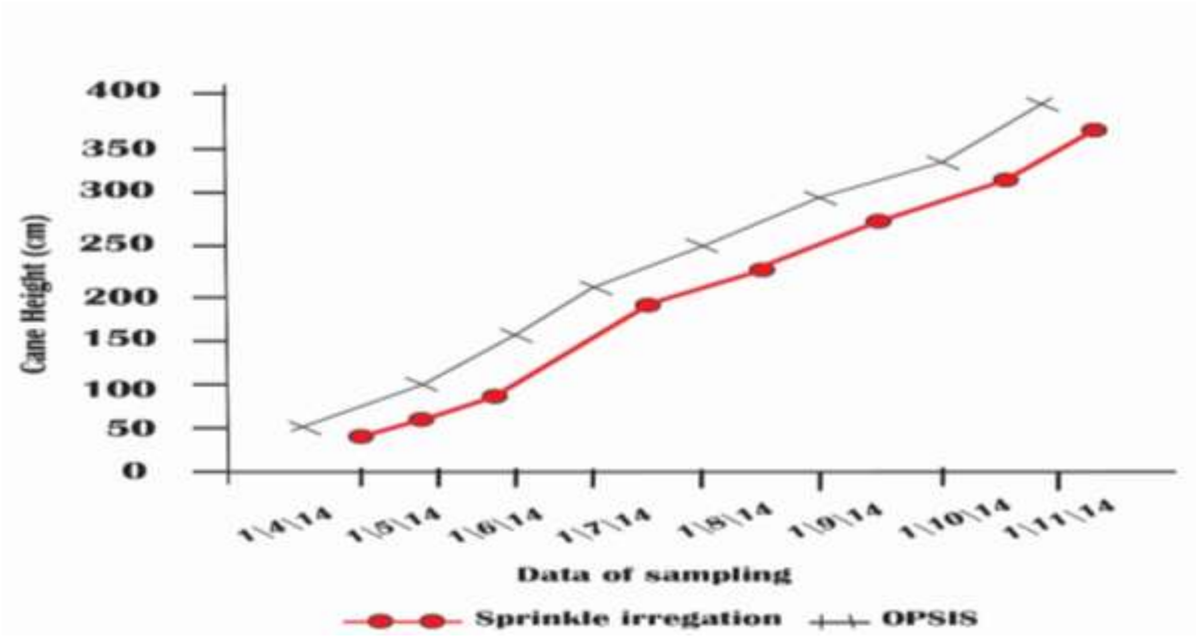


Fig (2)

2.1.2.2. Low-cost drip-LCDI

The Low-Cost Drip Irrigation system, branded as KB Drip, has a flow rate of 4 liters per hour. The system is put in the experimental plot with an emitter spacing of 50 cm and a single-row spacing of 1.5 m between rows. Both of these systems involved the use of lateral lines that were fitted with lateral end caps to ensure regular flushing of the whole lateral system. Flow control valves were placed at the start of the laterals. Pressure gauges were installed at the beginning and end of the submain to ensure the smooth operation of the system (Mahesh et al. 2022).

Table 4. Net irrigation and total water requirement of sugarcane

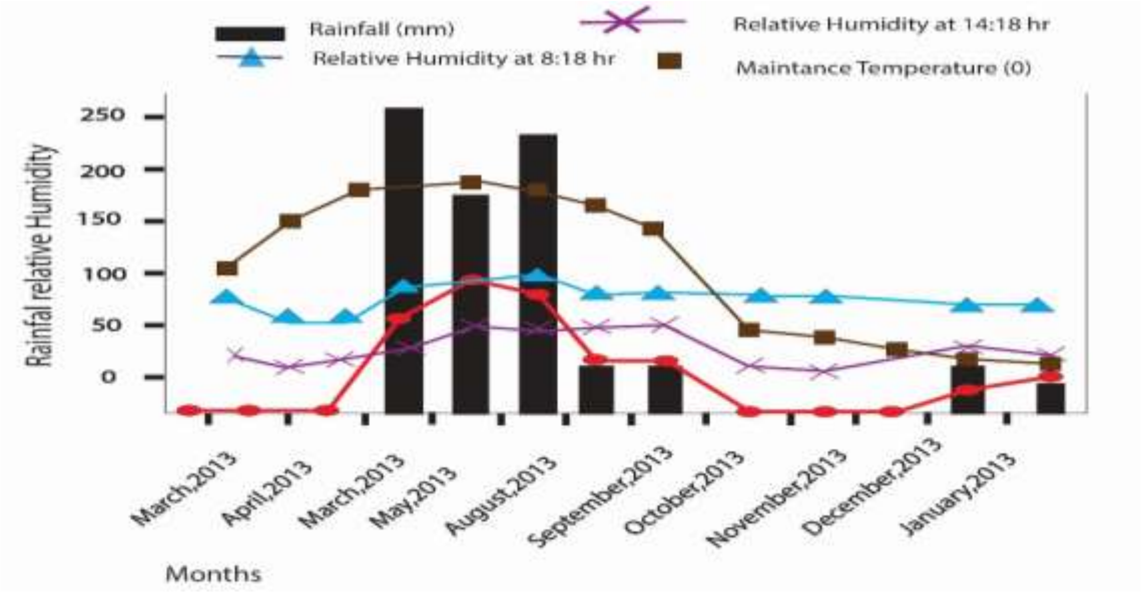
Characteristics\ months	Set	Aug	Jul	Jun	May	Apr	Mar	Feb	Jan	Dec	Nov	Oct	Total
Requirement for net irrigation (mm)	77.6	118.8	145.2	185.8	185.9	210.7	228.6	210.8	185.9 97	145.1	118.9	77.7	1510.3

2.1.2.3. Siphon irrigation

This irrigation technique utilizes 16 mm OD laterals, which are positioned 1.5 m apart, sourced from a submain PVC conduit. The laterals are positioned in furrows to facilitate irrigation, with a valve control or tap system incorporated into each lateral. The plot is irrigated by allowing water to flow down the slope. The primary benefit of this technology, as opposed to flood irrigation, is that it allows for irrigation to be applied to each row, hence reducing conveyance loss (Ulusoy 2021).

2.1.2.4. Flood irrigation

Surface flood irrigation has been implemented as a treatment for assessing alongside other irrigation systems (Li 2021).



2.1.3. Agronomic practices

The culture and management actions, such as earthing up, weeding, detaching, and propping, were uniformly carried out in all plots following the sugarcane growth calendar issued by the R&D Centre, EID parry. The recommended dose of nitrogen (N) and potassium (K) was delivered entirely through fertigation, whereas phosphorus (P) was applied as a basal application (Attri et al. 2022).

The study conducted a biometric assessment of cane growth and yield characteristics, such as number of tillers, germination count, cane girth, mailable cane, agronomic desirability, and cane yield, in both years. The assessment followed standard protocols (Rocha et al. 2019). In the 12th month, samples were collected for the small Mill Test (SMT) and various quality parameters, including brix, polarity, purity, fiber, and Pure Obtainable cane sugar yield, were determined using standard procedure. These measurements were recorded for both years according to the protocols outlined by Spencer and Meade in 1963. The crop underwent regrowth, known as ratooning, and the same methods were repeated (da Rocha et al. 2019).

Water stress tolerance in sugarcane

Environmental pressures constrain plant development and crop productivity. Drought is well recognized as the most harmful abiotic stress that negatively impacts crop output on a global scale

(Kumar et al. 2021). Sugarcane, a significant supplier of sugar and ethanol, is a crop that requires a huge amount of water and is extremely susceptible to water scarcity, sugarcane generates 8–12 tons of cane per ML of irrigation water. If there is a water deficit, productivity losses can reach up to 60%. Locations with a favorable rain regime for sugarcane growth and development centralize production areas (Dlamini 2021). In other places, crop production requires either supplemental or complete irrigation. Due to the rising occurrence, length, and severity of severe water scarcity, numerous big sugarcane crop development programs have decided to allocate resources towards developing water-use-efficient and water stress-resistant cultivars, as well as implementing water-use-efficient crop production systems (Coelho et al. 2019) Growing understanding of stress biology from genetic, agronomic, and molecular biology research in various crops, including sugarcane, is propelling the development of biotechnological approaches to produce water stress-tolerant and commercially valuable sugarcane varieties (Hernández-Pérez et al. 2021).

Plants have developed different strategies to tolerate drought, including altering their life cycle, adjusting their growth and development to match water availability, regulating overall plant functions to allocate resources for growth and stress adaptation, and evolving mechanisms to quickly and persistently respond to stress signals for improved stress tolerance (Verma et al. 2019). The expanding pool of knowledge has enabled the identification of pivotal genes associated with drought tolerance and the capacity to maintain growth in crops, such as sugarcane. Biotechnology and molecular breeding techniques are efficient for enhancing agriculture yield under drought conditions though there are molecular tools and methods available, as well as developments in our knowledge of stress responses, the task of engineering crops to be tolerant to drought is still a significant problem (Gomathi et al. 2020).

The challenges in developing drought-tolerant crop varieties suitable for commercial production conditions are twofold. Firstly, the complexity of plant responses to water deficit poses a significant obstacle (Garcia et al. 2021). Secondly, there is difficulty in identifying and utilizing genes and alleles with substantial effects, as well as the associated selection traits (Weksanthia et al. 2021). The predominant water stress reactions seen in sugarcane include leaf rolling, stomatal closure, suppression of stalk and leaf development, leaf senescence, and diminished leaf area (Taratima et al. 2020). Additionally, water stress halts both cell division and cell elongation processes in plants. Specifically highlight the impact on stem and leaf elongation, among other growth processes. Water deficiency has a lesser impact on root development compared to above-ground biomass (Silva et al. 2024).

Conclusion

Efficient water management is essential for ensuring the long-term viability and efficiency of sugarcane cultivation, particularly in light of growing water constraints. Farmers may significantly improve water-use efficiency and achieve better crop yields and healthier soils by using modern irrigation techniques like drip and sprinkler systems. These approaches not only preserve water but also guarantee the sustainable and profitable nature of sugarcane agriculture. To tackle the difficulties presented by the decreasing availability of water, it is crucial to embrace sustainable and innovative methods of managing water. Utilizing technologies such as soil moisture sensors, automated irrigation systems, and water recycling can effectively reduce the risks associated with water shortage, thereby guaranteeing the sustainability of sugarcane production in places with limited water resources An all-encompassing future-oriented strategy for water management is crucial to sustaining the productivity, environment sustainability, and long-term prosperity of sugarcane farming in the face of increasing worldwide water scarcity concerns.

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CONFLICT OF INTEREST STATEMENT

There is no conflict of interest.

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