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Optimized Subsurface Irrigation System: The Future of Sugarcane Irrigation

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Abstract: Climate change may harm the growth and yield of sugarcane (*Saccharum officinarum* L.) without the introduction of appropriate irrigation facilities. Therefore, new irrigation methods should be developed to maximize water use efficiency and reduce operational costs. OPSIS (optimized subsurface irrigation system) is a new solar-powered automatic subsurface irrigation system that creates a phreatic zone below crop roots and relies on capillarity to supply water to the root zone. It is designed for upland crops such as sugarcane. We investigated the performance of OPSIS for irrigating sugarcane and evaluated its performance against sprinkler irrigation under subtropical conditions. We conducted field experiments in Okinawa, Japan, over the period from 2013 to 2016 and took measurements during spring- and summer-planted main crops and two ratoon crops of the spring-planted crop. Compared with sprinkler irrigation, OPSIS produced a significantly higher fresh cane yield, consumed less irrigation water and provided a higher irrigation water use efficiency. We conclude that OPSIS could be adopted as a sustainable solution to sugarcane irrigation in Okinawa and similar environments.

Keywords: fresh cane weight; optimized subsurface irrigation (OPSIS); sprinkler irrigation; sugarcane; water use efficiency

1. Introduction

Sugarcane (*Saccharum officinarum* L.) is one of the most important crops in the world. It plays a vital economic role in sugar and bioenergy production and has an important social role in the rural communities of sugar-producing nations worldwide.

Climate change threatens the sustainability of most rainfed sugarcane farming systems [1]. Some authors have reported that certain climate change scenarios may harm sugarcane growth and yield without the introduction of appropriate irrigation facilities [1–4]. Rainfed sugarcane farming systems are gradually being replaced by irrigated farming systems wherever such transition is possible. In addition, low-efficiency irrigation systems are being replaced by high-efficiency systems to make sugarcane farming more economically sustainable. However, irrigation is one of the most expensive practices of sugarcane farming systems and can account for more than 25% of the production cost [5,6]. Therefore, the dimensions of sugarcane irrigation systems need to be adjusted for water conservation while simultaneously reducing operational costs.

Although sugarcane can tolerate some moisture stress, it still has a high water requirement—in the range of 1500 to 2500 mm per season [7]—in order to achieve yields close to the potential maximum [8,9]. Most importantly, sugarcane requires an evenly distributed water supply throughout its growing season to produce high yields. Even though sugarcane requires a high water supply, it is also susceptible to waterlogging, which reduces plant growth and yield [10]. Therefore, to maintain optimum soil moisture throughout the growing period and to achieve close to maximum yields, both appropriate irrigation and drainage facilities are vital in sugarcane fields.

Fresh water is often a scarce resource and sugarcane faces competition from other water uses; therefore, irrigation systems should be able to use water efficiently. However, if water is free or priced too low, farmers have no incentive to adopt capital-intensive technologies unless they confer other benefits (e.g., lower energy and labor costs, higher nutrient use efficiency).

Surface, overhead and drip irrigation methods are most commonly used to irrigate sugarcane crops [11] depending on physical characteristics, economic considerations and social and other considerations. The performance of irrigation systems directly affects crop performance, water use efficiency (WUE), cost of production and profit and is, therefore, of keen interest to farmers [12]. The same irrigation method and the same amount of water can produce significant differences in yield with different patterns of water application. Therefore, more uniform irrigation application needs to be targeted through design, continuous evaluation and maintenance practices [13]. However, continuous evaluation and maintenance require farmers to invest time and money that they may not have.

Traditionally, most sugarcane farming systems used surface (specifically furrow) irrigation because of its simplicity and low cost. But the increasing cost of energy and labor and the increasing demand for scarce water resources has led to greater adoption of overhead or drip irrigation methods. However, furrow irrigation is still the major method used worldwide [14]. The major drawbacks of furrow irrigation and the main reasons for its unpopularity among sugarcane farmers are the high labor requirement and low WUE stemming from percolation and tail-water losses [6,14]. Furrow irrigation is remarkably less efficient in light textured soils than overhead and drip irrigation systems. Although measures such as the use of low flow rates [15], surge irrigation [14,16] and local modifications [17] can increase the efficiency of furrow irrigation to a degree, such refinements have not been able to achieve satisfactory levels of efficiency and do not obviate the high labor requirement.

Sprinkler and drip irrigation methods utilize water pressure to irrigate sugarcane crops. A comparative study of surface drip irrigation, subsurface drip irrigation and surface irrigation of sugarcane reported that both surface and subsurface drip irrigation systems performed as well as surface irrigation systems in a few key areas such as plant growth and development and water savings [18]. Pires et al. [19] reported a higher fresh cane yield under subsurface drip irrigation than under rainfed farming. Shinde and Deshmukh [20] reported similar sugarcane yields from drip and rain gun sprinkler methods that exceeded those of surface irrigation but rain gun sprinkler irrigation consumed 33% more water than drip irrigation, which also gave a more uniform water distribution. In a comparison of different hydrant pressures (4.0, 4.5 and 5.0 bars) and nozzle sizes (2.4 mm $\times$ 4.4 mm and 2.4 mm $\times$ 4.8 mm), Dinka [21] reported large deep percolation losses (about 40%) in sprinkler irrigation in Ethiopia. This is a waste of water resources, energy and soluble nutrients, which results in increased production costs and environmental impacts.

Subsurface drip irrigation enhances growth and yield, not only through the precise application of the right amount of water, but also by maintaining adequate aeration of the root zone. Further, it promotes the effectiveness of applied fertilizers by minimizing losses through processes such as denitrification, deep percolation and runoff, which can occur with other irrigation methods. The optimum depth of subsurface drip lines varies between 10 and 80 cm depending on the soil type, soil depth and crop type, as capillary action ensures water uptake by upward water movement. With the same amount of water, subsurface drip irrigation wets an area about 50% larger than surface drip irrigation does. Mahesh et al. [22] reported that subsurface and surface drip irrigation can save 31% and 23% of water relative to surface irrigation. They further reported significantly higher sugarcane yield and WUE with subsurface fertigation than with surface irrigation with a conventional fertilizer application. However, subsurface drip irrigation entails some drawbacks, such as low germination if there is poor capillary movement, salinity, nozzle clogging and uneven water distribution [23]. Moreover, it does not always assure high efficiency and good yield because it requires an accurate design and a skilled operator [24]. Therefore, new methods or strategies must be introduced to subsurface irrigation systems to achieve better precision, while overcoming the inherent disadvantages of available subsurface irrigation methods.

Okinawa prefecture in Japan comprises many small islands with little or no surface water resources; therefore, sugarcane farming there requires water-efficient irrigation methods. However, drip irrigation—the most water-efficient method available—is not popular among sugarcane farmers in the prefecture because it is labor intensive, requires frequent monitoring and many farmers are aged and favor low-maintenance farming systems. Therefore, water saving irrigation methods that can be operated with minimum attention are required to make sugarcane farming systems in Okinawa more sustainable and economically viable.

The optimized subsurface irrigation system (OPSIS) is a new subsurface irrigation system for irrigating upland crops. It irrigates the root zone of the crop by capillarity [25]. OPSIS has two major components: a main water control system (including a solar-powered submersible pump, a water tank, a water supply column and a fertilizer tank) and a water distribution system (including a water distribution column at the head end of the field, perforated pipes buried parallel to the field surface to irrigate the field and PVC (Polyvinyl Chloride) or metal sheet to control seepage losses). Similar to the other subsurface irrigation systems, OPSIS is remarkable for its ability to eliminate surface runoff and evaporation [25]. Further, it significantly reduces percolation losses, which are common problems in other subsurface irrigation systems [25]. Because a small solar-powered pump is used to lift water and create a pressure head and because minimum operational activities are required [25], OPSIS offers the potential to drastically lower the operational costs of irrigation for sugarcane farmers in Okinawa.

In OPSIS, water flow is automatically triggered by solar radiation (as it uses a solar-powered pump) without any manual operation, however it irrigates (emits water through perforated pipes) based on the soil moisture's potential difference between the inside of the pipe and the outside soil. Further, it can remain in place during other field operations, including mechanical harvesting [25]. In that respect, OPSIS is compatible with the low-intervention requirements of Okinawan sugarcane farmers. Further, as the farmers irrigate their fields prescriptively (set timing and amounts), rainfall that occurs shortly after scheduled irrigation application leads to water wastage, whereas OPSIS irrigates only when required.

However, OPSIS is still new and has had little uptake in Okinawa as there is not yet sufficient information on it. OPSIS therefore needs to be compared with other irrigation methods in terms of both yield performances and water conservation, as water conservation is equally important in these small water-limited islands. Therefore, we conducted cultivation experiments in Okinawa to quantify the differences between OPSIS and conventional sprinkler irrigation systems in terms of water consumption and several growth and yield parameters.

2. Materials and Methods

2.1. Field Experiment

Field experiments were conducted in Itoman, Okinawa, Japan (26°7′59.07″ N, 127°40′52.32″ E) over a period from 2013 to 2016 in order to compare the performances of OPSIS and sprinkler irrigation in sugarcane cultivation under subtropical conditions. The climate of the Itoman area is classified as Cfa by the Köppen classification system [26] and is generally referred to as subtropical, with dry summers and mild cold winters. Climatic data of Naha, Okinawa (26°12′26″ N, 127°41′11″ E) were gathered from Japan's meteorological agency to assess the climatic conditions in Itoman during the study periods (Table 1). Daily rainfall of the experimental field was also measured to enable the precise calculation of the water use efficiency of irrigation treatments. The soil present at the experimental site is generally known to be dark red soils—called Shimajiri-Maji—which correspond to Udalfs, Udepts and Udolls in the United States Department of Agriculture Soil Taxonomy [27].

Table 1. Planting seasons and harvesting periods of sugarcane crops used to compare the performance of two irrigation methods and climatic conditions during the periods.

Planting Season	Crop Type	Planting Date	Harvesting Date	Rainfall (mm)	Max. T (°C)	Min. T (°C)	Cumulative SR (MJ/m^2)
Spring	Main crop	April 2013	March 2014	2234	15.5–34.8	10.3–28.9	5460
	First ratoon crop		January 2015	3599	14.9–33.9	9.8–28.8	4595
	Second ratoon crop		January 2016	2303	12.5–33.8	6.1–28.8	5499
Summer	Main crop	October 2013	January 2015	4529	14.9–33.9	9.8–28.8	6604

Rainfall—Total rainfall during the cropping period; Max. T—Range of maximum temperature during the cropping period; Min. T—Range of minimum temperature during cropping period; Cumulative SR—Cumulative solar radiation during the cropping period.

The sugarcane cultivar Ni21 used for this experiment is a Japanese cultivar that was developed to withstand strong winds from typhoons. The single-row planting method with 1.3 m spacing between rows was used in all treatments.

Experiments were conducted to observe growth and yield under two planting conditions—namely spring planting and summer planting—according to the local practice in Okinawa. Spring-planted sugarcane crop was extended to observe the growth and yield of two consecutive ratoon crops. In Okinawa, summer planting usually starts in September and spring planting in March. Both crops are harvested during January to March according to the requirement of sugarcane millers. Table 1 shows the planting and harvesting times of the crops studied. Figure 1 shows the field layout of the experiment.

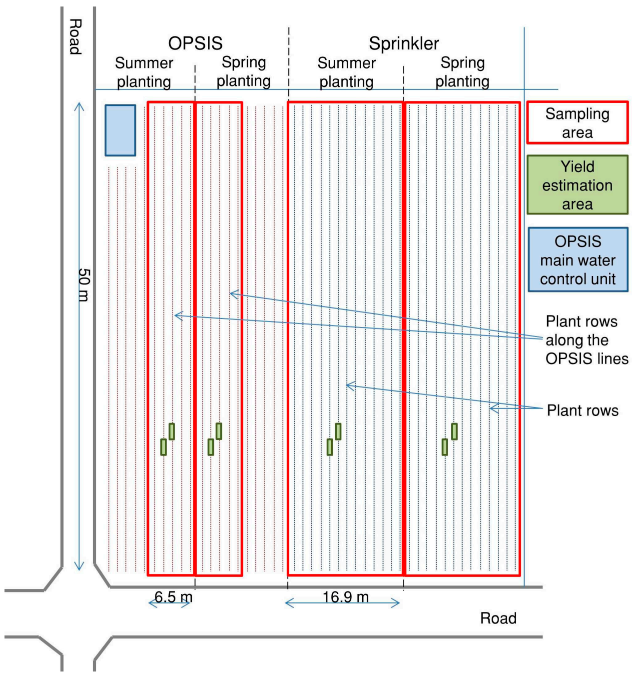

Figure 1. Field layout of experimental field (Teruya, Itoman) used to compare performance of optimized subsurface irrigation system (OPSIS) and conventional sprinkler irrigation in sugarcane cultivation.

In the OPSIS treatments, ten split applications of urea fertilizer were used at a rate of 350 kg/ha for the first 3 months of the crop. In the sprinkler irrigation treatment, the same amount of fertilizer was added as two splits, at one and two months after planting, following the regular fertilizer application practice in Okinawa.

2.2. Irrigation System Installation

For the OPSIS treatments, two plots of 6.5 m × 50 m were prepared by installing five OPSIS lines at 1.3 m spacing. Before planting, the main water control system was established [25]. A concrete water tank stored water and 100 mm PVC pipes were used to make a water supply column, water distribution column and fertilizer tank. The water control mechanism of the water supply column used a 50 mm PVC pipe (inner pipe) and a 6.5 mm flexible pipe [25]. An automatic fertilizer tank [25] supplied fertilizer to the irrigation system [25]. The water distribution column, which feeds five irrigation supply lines [25], was set vertically at the head end of the field. The irrigation supply lines were made of 50-mm flexible perforated pipe, which was simultaneously laid together with 45-cm-wide PVC sheets (seepage barrier) using the newly developed OPSIS system laying attachment [25]. The irrigation lines were laid 45 cm below the soil surface. The seepage barrier was laid below the supply line forming an open trapezoidal cross-section [25]. The height, top width and bottom width of the trapezoid were 15, 30 and 12 cm, respectively. In OPSIS treatments, automatic irrigation was practiced during the crop growing period and stopped in October until harvesting the crop.

For the sprinkler irrigation treatments, two plots of 16.9 m × 50 m were prepared by installing commercially available impact-type sprinklers. Irrigation was practiced on a fixed-interval irrigation schedule similar to the common practice in Okinawa.

2.3. Plant Growth and Yield Sampling

Plant height and cane diameter of the summer-planted main crop and the first ratoon crop of the spring-plant were measured at monthly intervals from April 2014 to January 2015 using non-destructive sampling. The distance from the soil surface to the +1 dewlap (plant height; [28]) and the diameter of the middle internode of the randomly selected primary shoots of five plants in the central three rows of each plot were measured. Linear mixed-effects analysis was performed—using the lme4 package [29] of R statistical software (R Foundation for Statistical Computing, Vienna, Austria) [30]—to compare the effect of irrigation method on height and diameter. In the linear mixed-effect analysis, irrigation method was used as the fixed effect and crop type (main crop or ratoon) was used as the random effect. Interaction was ignored. Residual plots were visually inspected to check the normality of errors. Likelihood ratio tests of full models (with the effect of irrigation) and null models (without the effect of irrigation) were used to test for significant differences between means.

During harvesting of the spring- and summer-planted main crops and the two ratoon crops, a 5.2 m^2 area was randomly selected in each plot to measure yield. Fresh cane weight was measured on a top-loading balance, average cane diameter of the harvest with a vernier caliper and average millable cane length of the harvest with a measuring tape. The Brix value of the cane juice extracted from the middle internode (estimate of sugar content) was measured with a hand-held refractometer and the values were corrected to 20 °C. The number of millable stalks was also counted as part of the yield survey. Linear model analysis was performed using R statistical software to compare the effect of irrigation method and planting season/crop type on measured yield parameters except the number of millable stalks. Linear models for each measured parameter were set as a function of irrigation method and planting season/crop type. The interaction between irrigation method and crop type/planting season was ignored. Poisson regression analysis using the MASS package [31] of R statistical software was used to compare the effect of irrigation method and planting season/crop type on the number of millable stalks. Mean separation was performed using the least significant difference (LSD) comparison of the agricolae package [32] of R.

2.4. Measurement of Irrigation Water Use

Irrigation water use in the first and second ratoon crops under sprinkler irrigation and OPSIS was surveyed during the growing periods. Irrigation of the first ratoon crop was started in April 2014 and continued until October 2014. Irrigation of the second ratoon crop was started in February 2015 and continued until October 2015. The amount of irrigation consumed in the OPSIS treatment was measured using water level recorders attached to the main water tank. Water level was recorded at 1-h intervals and converted into a daily irrigation amount. The amount of irrigation water used in the sprinkler irrigation treatment was measured during each irrigation event and recorded.

2.5. Water Use Efficiency

Daily rainfall was measured using a recording rain gauge that was installed at the site. Effective rainfall—the portion of rainfall that can be effectively used by the plants—was calculated using the procedure as explained by Brouwer and Heibloem [7]. Total and irrigation water use efficiencies were calculated using Equations (1) and (2):

$$\text{Water Use Efficiency (WUE)} = \frac{\text{Cane yield (t/ha)}}{\text{Total water applied (cm)}} \tag{1}$$

$$\text{Irrigation Water Use Efficiency (IWUE)} = \frac{\text{Cane yield (t/ha)}}{\text{Total irrigation water applied (cm)}} \tag{2}$$

3. Results

3.1. Plant Height during Crop Growth

Figure 2 shows how irrigation method affected the average plant height of the main summer-planted crop and the first ratoon crop of the spring-planted crop. In both crops, plant height shows the usual sigmoidal growth pattern under both irrigation methods. Linear mixed-effects analysis revealed that irrigation method significantly affected plant height (χ^2 = 44.36, $p < 0.001$), with OPSIS increasing the plant height by 34.0 ± 3.4 cm, which was an increase of approximately 12% compared to that from the sprinkler irrigation.

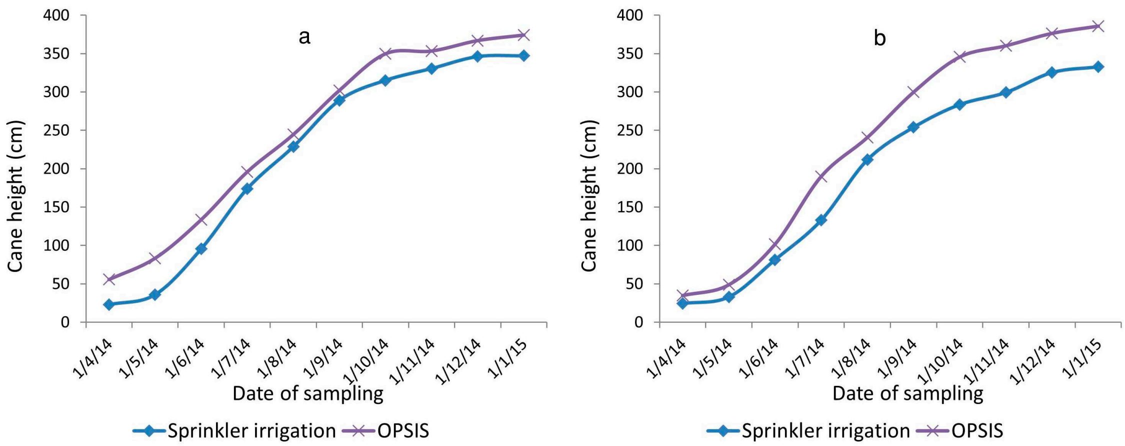

Figure 2. Average plant height of sugarcane cultivar Ni21 as affected by irrigation method in (**a**) the summer-planted main crop and (**b**) the first ratoon crop of spring-planted sugarcane.

3.2. Cane Diameter during Crop Growth

Figure 3 shows how irrigation method affected the average cane diameter of the main summer-planted crop and the first ratoon crop of the spring-planted crop over the course of crop development. Linear mixed-effects analysis revealed that irrigation method did not have a significant effect on cane diameter ($\chi^2 = 0.10$, $p = 0.75$).

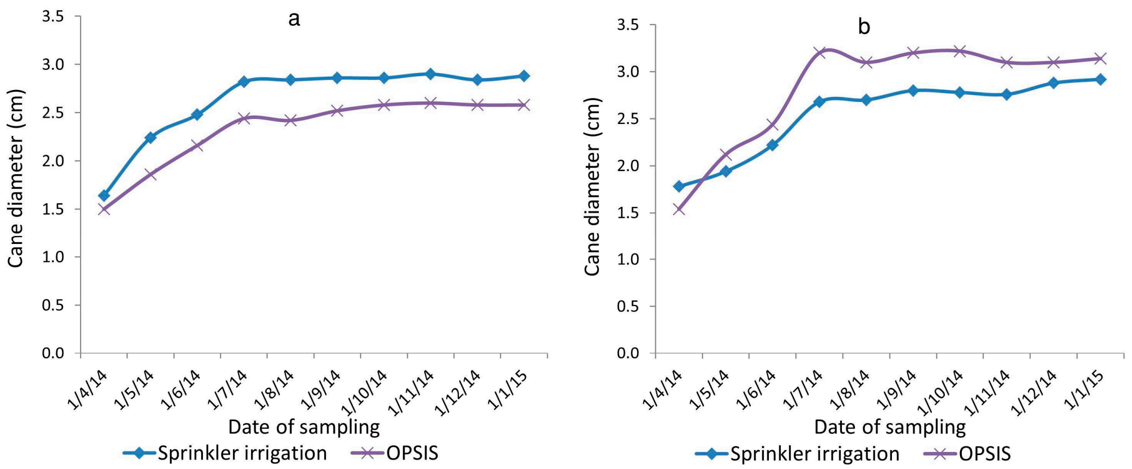

Figure 3. Average cane diameter of sugarcane cultivar Ni21 as affected by irrigation method in (**a**) the summer-planted main crop and (**b**) the first ratoon crop of spring-planted sugarcane.

3.3. Fresh Cane Yield

The OPSIS-irrigated crops all had a higher fresh cane yield than the sprinkler-irrigated crops (Figure 4): by 9% in the spring-planted main crop, 27% in the summer-planted main crop, 44% in the first ratoon crop and 20% in the second ratoon crop. The linear model analysis revealed that irrigation method and crop type significantly affected the fresh cane yield ($F(2, 5) = 20.3$, $p = 0.004$). OPSIS produced significantly higher yield than sprinkler irrigation (by 23.0 ± 4.7 t/ha, $p = 0.005$). Both main crops recorded higher yields (by 8.6 ± 2.1 t/ha, $p = 0.009$) than the ratoon crops.

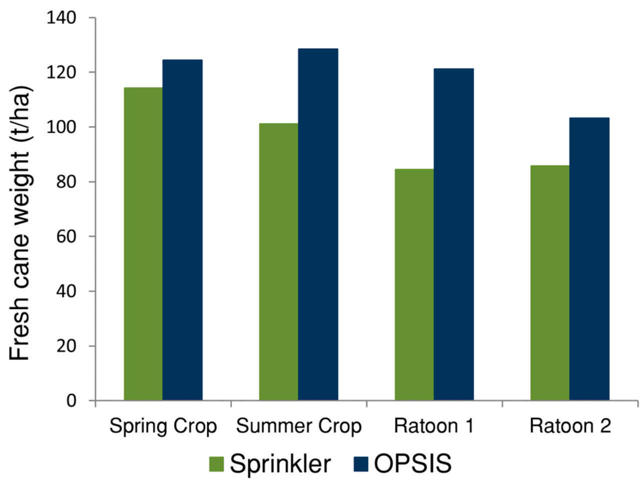

Figure 4. Fresh cane yield of sugarcane cultivar Ni21 as affected by irrigation method.

3.4. Millable Cane Length

Figure 5 shows the how irrigation method affected average millable cane length in the spring-planted crop, summer-planted crop and the first and second ratoon crops of the spring-planted sugarcane. The OPSIS-irrigated crops all had a higher average millable cane length than the sprinkler-irrigated crops (Figure 5): by 13% in the spring crop, 14% in the summer crop, 23% in the first ratoon crop and 2% in the second ratoon crop. The linear model analysis revealed that OPSIS significantly increased the average cane length of the harvest (by 29.8 ± 11.1 cm, $p = 0.04$) relative to sprinkler irrigation.

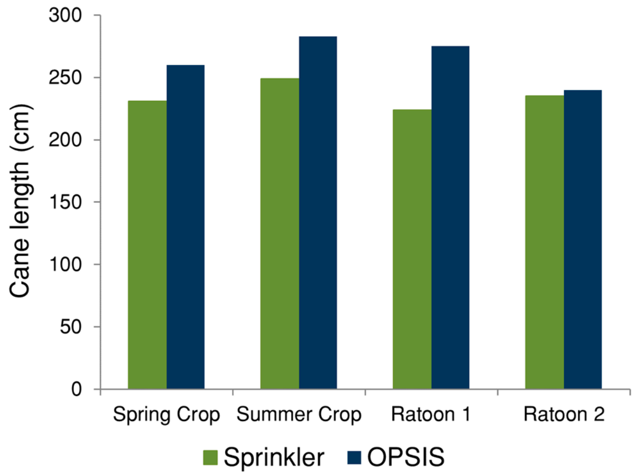

Figure 5. Average millable cane length of sugarcane cultivar Ni21 as affected by irrigation method.

3.5. *Cane Diameter at Maturity*

The cane diameter of the middle internode (Figure 6) was not significantly affected by irrigation type ($F(2, 5) = 2.2$, $p = 0.21$).

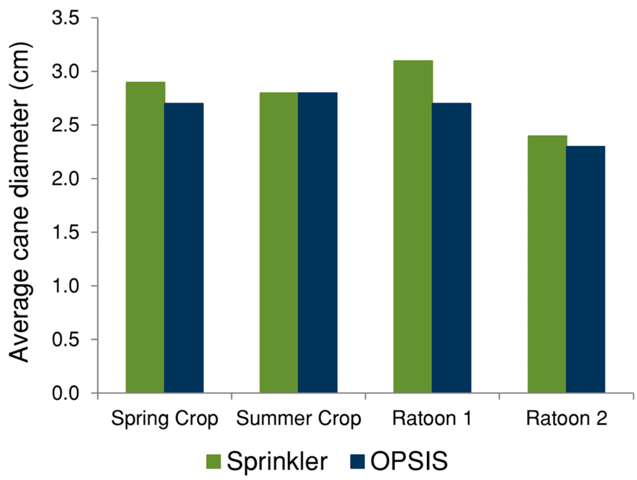

Figure 6. Average cane diameter of sugarcane cultivar Ni21 as affected by irrigation method.

3.6. *Number of Millable Stalks*

The number of millable stalks (Figure 7) was greater with OPSIS irrigation in the spring-planted crop (+2%), summer-planted crop (+14%) and second ratoon crops (+31%) than with sprinkler irrigation. No difference in millable stalk number was observed between irrigation types in the first ratoon crop. The Poisson regression analysis revealed that OPSIS significantly increased the number of millable cane stalks ($p < 0.001$) relative to sprinkler irrigation.

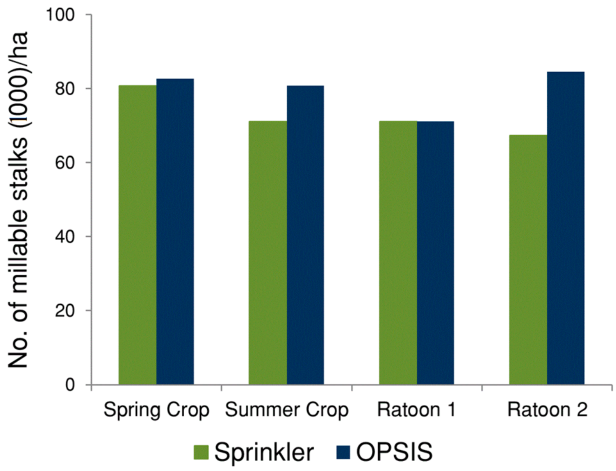

Figure 7. Number of millable stalks of sugarcane cultivar Ni21 as affected by irrigation method.

3.7. Brix Value

Figure 8 shows how irrigation method affected the Brix value of juice extracted from the middle internode in the four crops. The linear model analysis revealed that irrigation method and crop type did not affect the Brix value of cane juice ($F(2, 5) = 0.62$, $p = 0.57$).

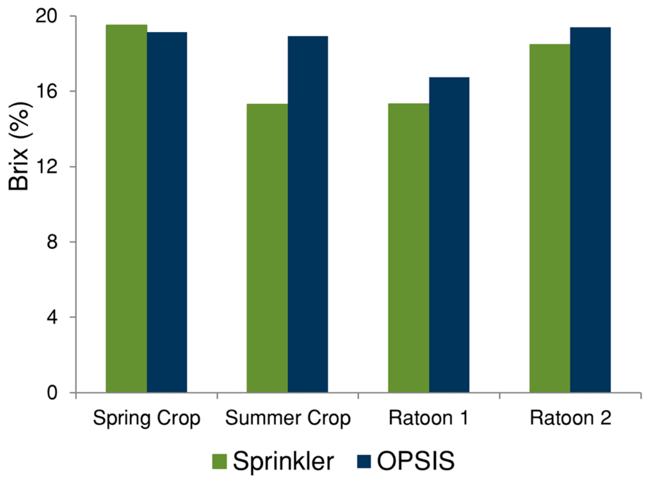

Figure 8. Average Brix value of cane juice of sugarcane cultivar Ni21 as affected by irrigation method.

3.8. Irrigation Water Use

From April 2014 to January 2015, the research field received 3342 mm of rainfall (higher than the average of 2200 mm for the area), of which an estimated 2474 mm was effective rainfall. Therefore, both irrigation methods consumed low amounts of irrigation water during the growing period of the first ratoon crop. However, the results showed that OPSIS (82 mm) consumed only 46% of the amount of water that was consumed by sprinkler irrigation (178 mm). During the second ratoon crop, the field received 2239 mm of rainfall, of which an estimated 1545 mm was effective. During this period OPSIS (323 mm) used 79% of the water used by sprinkler irrigation (409 mm). In the sprinkler irrigation, although antecedent rainfall was taken into consideration, irrigation timing followed the irrigation schedule decided in the region. Therefore, more irrigation water was used than needed. On the other hand, OPSIS does not use much water when soil moisture is near saturation. Therefore, OPSIS used less water than sprinkler irrigation and the difference was greater when rainfall was above average. The difference is attributed to OPSIS having more precise application, an absence of runoff and minimal evaporation compared with sprinkler irrigation.

3.9. Water Use Efficiency

In the first ratoon crop, OPSIS recorded irrigation water use efficiency (IWUE) of 14.8 t/ha/cm, which was 3.1 times that of sprinkler irrigation (4.8 t/ha/cm). Because of the high rainfall received during this season, the total WUE was low in both methods: 0.47 t/ha/cm in OPSIS and 0.32 t/ha/cm in sprinkler irrigation. During the second ratoon crop, OPSIS recorded an IWUE of 3.2 t/ha/cm, which was 1.5 times that of sprinkler irrigation (2.1 t/ha/cm). The total WUEs of OPSIS and sprinkler irrigation were 0.55 and 0.44 t/ha/cm respectively.

4. Discussion

4.1. Crop Yield

Our results confirm that the sugarcane yield was higher with OPSIS than with conventional sprinkler irrigation and the higher yield was achieved by the increase in millable cane length and the number of millable canes.

In previous studies, optimum soil moisture [33,34] and nutrient supply [35,36] have been found to increase the number of millable stalks—a significant contributor to the economic yield—because water and nutrient stresses reduce tiller production and increase tiller mortality. Because water availability directly influences cell turgor [37] and thus cell growth and development, increased plant height and canopy development of sugarcane have been reported when moisture and nutrient stresses are removed [34,38]. Optimum soil moisture [39] and nutrient availability [40] have also been shown to increase the photosynthetic rate in sugarcane.

Juan et al. [39] examined mean net photosynthetic rate in the sugarcane cultivar Liucheng 05-136 under six irrigation methods and found that photosynthetic rate was highest in the subsurface drip irrigation treatment, which was 58% higher than with no irrigation, 24% higher than with pipe irrigation, 13% higher than with sprinkler irrigation, 10% higher than with micro-sprinkler irrigation and 3% higher than with surface drip irrigation. They concluded that irrigation method significantly affects the photosynthetic rate of sugarcane plants. Further, using Path analysis, they reported soil water content, air temperature and soil fertility as the main environmental factors influencing sugarcane net photosynthetic rate, with some differences in these among irrigation methods. Fertigation improves the utilization of fertilizer and therefore can boost plant growth, increase the number of effective tillers, promote stalk elongation and diameter enlargement and ultimately increase the millable cane yield [35]. Similarly, Sivanappan [41] reported that soil fertility limitations, poor water management and unbalanced nutrient management are the major barriers to achieving maximum potential sugarcane yields. Proper irrigation and nutrient management are therefore essential to achieving sugarcane yields close to the potential. The higher yields in furrow irrigation than in rainfed conditions [42,43], in surface and subsurface drip irrigation than in surface irrigation [18,44] and in subsurface drip irrigation than in sprinkler irrigation [45] are on par with the importance of water and nutrient management in achieving higher yields near close to the potential yield.

Fertigation is an effective method for increasing sugarcane yield as it manages both water and nutrients more effectively than conventional fertilizer applications. A study reported a 32% higher sugarcane yield with drip fertigation than with conventional fertilizer applications (without drip irrigation) and a 23% higher yield than with drip irrigation plus a conventional fertilizer application [35]. Abdel Wahab [46] reported higher growth and yield performances of sugarcane with fertigation than with conventional fertilizer applications, in both cases using a gated pipe surface irrigation system. Similarly, in the current study, OPSIS results in a higher growth and yield of sugarcane than sprinkler irrigation. Since all physiological processes depend on water and nutrient availability and the adverse effects of water and nutrient stress on physiological processes [47] and canopy development [48] are well understood, it is clear that the higher growth and yield of sugarcane from OPSIS derives from the better water and nutrient management it affords.

4.2. Water Use Efficiency

Our results confirm that OPSIS achieves a higher total WUE and IWUE than sprinkler irrigation. Kumawat et al. [49] reported 56% higher WUE with drip irrigation (5.96 t/ha/cm) than with surface irrigation (3.32 t/ha/cm), as well as minimal water losses and higher yields. Even with a yield penalty due to increased residues, the use of residue as a cover significantly increased IWUE relative to bare soil by cutting evaporation losses [50,51]. Gupta and Singh [52] reported that the ability of drip irrigation to significantly increase IWUE relative to furrow irrigation was due to both lower water use and higher yields (attributed to more millable stems and increases in both stem length and diameter). Similarly, in our study, OPSIS resulted in higher IWUE due to fewer water losses and higher yields than sprinkler irrigation. It also returned a higher total WUE and higher IWUE than sprinkler irrigation, which derives from both higher crop yield and lower irrigation water consumption than in sprinkler irrigation.

Under rainfall conditions close to the average (during ratoon 2), the water savings were less than when rainfall was above average (during ratoon 1). This result suggests that there were water losses, probably due to percolation, when water was close to average. Therefore, measures should be taken to control the percolation losses. Gunarathna et al. [25] suggested changing the solar-radiation–triggered automatic operation mechanism to a soil-moisture–based automatic operation mechanism to minimize percolation losses.

5. Conclusions

This study showed that OPSIS offers advantages over sprinkler irrigation for sugarcane cultivation in Okinawa in respect of both sugarcane yield and WUE. Compared with sprinkler irrigation, OPSIS produced significantly taller plants and thus significantly longer millable stalks and significantly more millable stalks. Therefore, OPSIS achieved significantly higher fresh cane weight using less irrigation water than did sprinkler irrigation. OPSIS is a water-conserving irrigation technique that can irrigate sugarcane crops with minimal operational cost, energy consumption and human intervention. Therefore, it may be a sustainable alternative for sugarcane crop irrigation in Okinawa and similar subtropical environments.

6. Recommendations

Further studies are needed to validate the long-term viability of OPSIS as a sustainable alternative to current irrigation methods used in sugarcane farming systems. We need to confirm that the benefits revealed in the current study hold under different climatic, soil and management conditions and, wherever possible, identify improvements to the system.

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