EFFICIENT WATER SUPPLY FOR SUGARCANE PRODUCTION UNDER DRIP IRRIGATION SYSTEM

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Suranaree University of Technology has approved this thesis submitted in partial fulfillment of the requirements for a Master's Degree.

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คำสำคัญ: อ้อย/การจัดการน้ำ/ระบบเซ็นเซอร์ไร้สาย/หลักสมดุลน้ำ

อ้อยมีการปลูกมากที่สุดในภาคตะวันออกเฉียงเหนือ โดยทั่วไปจะมีการปลูกและเก็บผลผลิตในช่วงเดือนธันวาคมถึงมีนาคม ซึ่งเป็นช่วงมีปริมาณน้ำฝนน้อย อ้อยที่ปลูกหรืองอกใหม่จึงมักประสบปัญหาขาดแคลนน้ำอย่างรุนแรง ซึ่งมีผลกระทบโดยตรงต่อการผลิตอ้อยทั้งด้านคุณภาพและปริมาณ ดังนั้นการให้น้ำแก่อ้อยโดยระบบน้ำหยดจะมีประสิทธิภาพมากที่สุดในช่วงต้นของการเพาะปลูก เพราะนอกจากจะทำให้ดินมีความชื้นที่พอเหมาะ ลดผลกระทบของความแห้งแล้งต่อการเจริญเติบโต ลักษณะทางสรีรวิทยา และผลผลิต อย่างไรก็ตามการให้น้ำในระบบน้ำหยดจะมีประสิทธิภาพมากหรือน้อยขึ้นอยู่กับการควบคุมการให้น้ำที่มีประสิทธิภาพ งานวิจัยนี้มีวัตถุประสงค์เพื่อศึกษาผลของการให้น้ำหยดต่อการเจริญเติบโต ผลผลิต กระบวนการทางสรีรวิทยาของอ้อย และเปรียบเทียบผลของการให้น้ำแบบหยดที่ควบคุมการให้น้ำโดยหลักสมดุลน้ำ และระบบเซ็นเซอร์ไร้สายต่อการเจริญเติบโต ผลผลิตและประสิทธิภาพการใช้น้ำของอ้อย งานทดลองแบ่งออกเป็น 3 ส่วน โดยทดลองในอ้อยพันธุ์ขอนแก่น 3 การทดลองที่ 1 มีการวางแผนการทดลองแบบ RCBD จำนวน 3 ซ้ำ มีการให้น้ำ 3 กรรมวิธี ได้แก่ 1) ไม่ให้น้ำ (สภาพน้ำฝน) 2) การให้น้ำครึ่งหนึ่งตามหลักสมดุลน้ำ และ 3) การให้น้ำเต็มที่ตามหลักสมดุลน้ำ ผลการศึกษาพบว่า การปลูกอ้อยในระบบน้ำหยดโดยการให้น้ำแบบเต็มที่ตามหลักสมดุลน้ำทำให้การเจริญเติบโตและผลผลิตอ้อยเฉลี่ยสูงถึง 19.7 ตันต่อไร่ ซึ่งผลผลิตสูงกว่ากรรมวิธีการให้น้ำครึ่งหนึ่งตามหลักสมดุลน้ำและสภาพน้ำฝน 19.4% และ 31.1% ตามลำดับ การทดลองที่ 2 ดำเนินการทดสอบภายใต้สภาวะโรงเรือน มีการวางแผนการทดลองแบบ RCBD จำนวน 3 ซ้ำ มีการให้น้ำ 3 กรรมวิธี ได้แก่ 1) การให้น้ำเต็มที่ (ควบคุม) 2) สภาวะขาดน้ำที่อายุ 3 เดือน และ 3) สภาวะขาดน้ำที่อายุ 7 เดือน ผลการศึกษาพบว่า สภาพการให้น้ำเต็มที่ทำให้มีลักษณะทางสรีรวิทยา (อัตราการสังเคราะห์แสง อัตราการคายน้ำ และการเปิด-ปิดปากใบ) ที่ดีตลอดระยะเวลาการทดลอง แต่การขาดน้ำทั้ง 2 ช่วงมีผลเสียอย่างมากต่อลักษณะทางสรีรวิทยาโดยเฉพาะในช่วงเวลาที่มีการขาดน้ำ และทำให้การเจริญเติบโตและผลผลิตลดลง โดยการขาดน้ำที่อายุ 7 เดือนมีผลทำให้ผลผลิตลดลงมากกว่าการขาดน้ำที่อายุ 3 เดือน เมื่อเปรียบเทียบการให้น้ำเต็มที่ผลผลิตอ้อยสูงกว่าสภาวะขาดน้ำที่ 3 เดือน และ 7 เดือน 44.4% และ 52.6% ตามลำดับ การทดลองที่ 3 ได้ดำเนินการในดิน 2 ชนิด ได้แก่ ดินร่วนเหนียวปนทราย และดินร่วนทราย มีการวางแผนการทดลองแบบ RCBD จำนวน 3 ซ้ำ มีการให้น้ำ 4 กรรมวิธี ได้แก่ 1) การควบคุม (ไม่ให้น้ำ) + ปุ๋ยทางดิน 2) ระบบน้ำหยดควบคุมโดยหลักสมดุลน้ำ + ปุ๋ยทางดิน 3) ระบบน้ำหยดควบคุมโดยหลักสมดุลน้ำ + ปุ๋ยระบบน้ำ

และ 4) ระบบน้ำหยดควบคุมโดยเซ็นเซอร์ + ปุ๋ยระบบน้ำ ผลการศึกษาพบว่า ระบบน้ำหยดที่ควบคุมโดยเซ็นเซอร์มีผลผลิตสูงที่สุด 19.0 และ 21.3 ตันต่อไร่ และสูงกว่าการไม่ให้น้ำ 55.7% และ 26.0% ในดินร่วนเหนียวปนทราย และดินร่วนทราย ตามลำดับ สำหรับประสิทธิภาพการใช้น้ำชลประทาน การให้น้ำในระบบน้ำหยด + ปุ๋ยทางระบบน้ำ ทั้ง 2 กรรมวิธี (เซ็นเซอร์และหลักสมดุลน้ำ) ผลผลิตอ้อยไม่แตกต่างกันในทางสถิติ แต่การควบคุมโดยเซ็นเซอร์สามารถเพิ่มประสิทธิภาพการใช้น้ำชลประทานได้มากกว่าระบบน้ำหยดควบคุมโดยหลักสมดุลน้ำ เนื่องด้วยการใช้เซ็นเซอร์ควบคุมการให้น้ำสามารถประหยัดน้ำได้ 7.1 และ 15.5% ในดินร่วนทรายและดินร่วนเหนียวปนทราย ตามลำดับเทียบกับการควบคุมการให้น้ำตามหลักสมดุลของน้ำ จากผลการทดลองสามารถสรุปได้ว่าการควบคุมการให้น้ำโดยเซ็นเซอร์ไร้สายมีความแม่นยำมากกว่าการใช้หลักสมดุลน้ำ มีความสะดวกและใช้งานได้ง่ายกว่า อย่างไรก็ตามค่าใช้จ่ายของเซ็นเซอร์ไร้สายยังคงมีราคาแพงสำหรับเกษตรกรรายย่อย

สาขาวิชาเทคโนโลยีการผลิตพืช

ปีการศึกษา 2565

ลายมือชื่อนักศึกษา ____________________

ลายมือชื่ออาจารย์ที่ปรึกษา ____________________

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PENNAPA SRISAWAT : EFFICIENT WATER SUPPLY FOR SUGARCANE PRODUCTION UNDER DRIP IRRIGATION SYSTEM. THESIS ADVISOR : ASST. PROF. THITIPORN MACHIKOWA, Ph.D., 76 PP.

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Sugarcane is mostly grown in the Northeast which is usually cultivated and harvested from December to March during a period of low rainfall. New planting or regerminated sugarcane often face a severe water deficit which directly impacts both quality and quantity of sugarcane production. Therefore, the sugarcane practice with drip irrigation is most effective in the early stage of planting since it can maintain optimal soil moisture and reduce the effects of drought stress on growth, physiological processes, and yield. However, the efficiency of drip irrigation also depends on the water controlling method. This research aimed to study the effects of drip irrigation on growth, yield, and physiological process of sugarcane and to compare the effects of the drip irrigation controlling method between a water balance model and a wireless sensor system on growth, yield and water use efficiency of sugarcane. A series of 3 drip irrigation experiments was conducted using sugarcane cultivar Khon Kaen 3 (KK3). The 1st experiment was conducted under field conditions using a randomized complete block design (RCBD) with 3 replications. The treatments were 3 irrigation methods including i) Control (rainfed condition), ii) Drip irrigation with half water supply, and iii) Drip irrigation with full water supply. The results showed that drip irrigation with full water supply produced the highest growth and yield (19.7 tons/rai) which was 19.4% and 31.1% higher than drip irrigation with half water supply and rainfed conditions, respectively. The 2nd experiment was conducted under greenhouse conditions. The experimental design was RCBD with 3 replications. The treatments were 3 irrigation methods including i) Well irrigated (control) ii) Water deficit at 3 months after planting (MAP), and iii) Water deficit at 7 MAP. The results showed that the well-irrigated treatment could maintain suitable physiological processes (photosynthesis rate, transpiration rate, and stomatal conductance) at all growth stages. Both water deficit conditions had significantly negative effects on physiological processes especially during their water deficit periods which consequently had negative impacts on growth and productivity. The water deficit at 7 MAP had more negative effect on yield than the water deficit at 3 MAP. The cane yield of well irrigated treatment was 44.4% and 52.6% more than water deficit conditions at 3 MAP and 7 MAP, respectively. The 3^{rd} experiment was conducted in 2 soil textures (sandy clay loam (SCL) and loamy sand (LS)). The experimental design was RCBD with 3 replications. The treatments were 4 irrigation methods including i) Control (no irrigation) + Soil fertilizer application ii) Drip irrigation controlled by water balance model + Soil fertilizer application, iii) Drip irrigation controlled by water balance model + Fertigation, and iv) Drip irrigation system controlled by sensor + Fertigation. The results showed that the drip irrigation controlled by the sensor produced the highest yields of 19.0 and 21.3 tons/rai which was 55.7% and 26.0% higher than no irrigation in SCL and LS soils, respectively. Comparing the irrigation controlling methods, found that there was no significant difference between either irrigation method (sensor or water balance model) in cane yield, but the drip irrigation controlled by the wireless sensor had higher irrigation water use efficiency (IWUE) than the drip irrigation controlled by the water balance model since it used 7.1 and 15.5% less water than the drip irrigation controlled by water balance model in LS and SCL soil, respectively. From the results, it can be concluded that drip irrigation controlled by the wireless sensor had higher precision for irrigation control than the water balance model. Additionally, it was more convenient and easier to use than the water balance model. However, the cost of the wireless sensor was still expensive for small scale farmers.

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LIST OF ABBREVIATIONS

AS	=	Apparent Specific Gravity
Av.P	=	Available P
Aw	=	Available Moisture Content
AWHC	=	Available water holding capacity
DAP	=	Day after planting
EC	=	Electrical conductivity
Epan	=	Class A Pan Evapotranspiration
ETc	=	Crop evapotranspiration
ETp	=	Potential evapotranspiration
Ex.Ca	=	Exchangeable Ca
Ex.K	=	Exchangeable K
Ex.Mg	=	Exchangeable Mg
FC	=	Field Capacity
FUE	=	Fertilizer use efficiency
IWUE	=	Irrigation water use efficiency
Kc	=	Crop coefficient
Kp	=	Class A Pan coefficient
kPa	=	Kilopascal
LS	=	Loamy sand soil
LWP	=	Leaf water potential
MAP	=	Month after planting
NMC	=	Number of millable canes
OM	=	Organic matter
Pv	=	Available Moisture Content
PWP	=	Permanent Wilt Point
SCL	=	Sandy clay loam soil

LIST OF ABBREVIATIONS (Continued)

SCMR	=	SPAD chlorophyll meter reading
SWHC	=	Soil water holding capacity
TSS	=	Total Soluble Solids
TVD	=	Top Visible Dewlap
WB	=	Water Balance Model
WM	=	Watermark sensor
WSN	=	Wireless sensor network

CHAPTER I
INTRODUCTION

1.1 The provenance and important

Sugarcane is an important industrial crop in Thailand where it is the fourth largest sugarcane producer in the word and the second largest exporter of sugar. Sugarcane is mostly grown in Kanchanaburi, Nakhon Sawan, Nakhon Ratchasima, Lop Buri, Udon Thani, Suphan Buri, Kamphaeng Phet and Khon Kaen province. There were 4.75 million rai of sugarcane cultivation areas in the northeast of Thailand during 2016/17 with an average yield of 9.31 tons per rai that was less than the other regions of the country (Office of Cane and Sugar Board, 2017).

Northeast of Thailand has the most suitable temperature for growing sugarcane which ranges between 26–35 degrees celsius. The production efficiency may be limited by chemical and physical properties of the soil, slope of areas, availability of water, and unpredictable rainfall. The soil in this area is mostly sandy soil that has low water holding capacity and nutrient absorption, and high drainage causing water shortage. In terms of water requirement, most of the sugarcane cannot receive enough water in every season because it needs water for 10 months but only receives rainfall for 5–6 months. If the sugarcane receives sufficient water throughout the growth period, the growth and yield will be significantly improved.

The suitable irrigation system would be the drip irrigation system, which is proved to be the most effective irrigation system by many researches. However, it is not yet adapted well by the farmers who cannot control water supply precisely causing loss or lack of water and low water use efficiency. In all irrigation systems, water supply can be controlled by 2 methods. The first method is based on the water balance model. In this method, the crop evapotranspiration (ETc) is estimated from weather conditions and crop coefficient (Kc), and the soil water holding capacity (SWHC) will be used to define the water supply pattern. Another method is to monitor the soil moisture content during the irrigation period. If the soil moisture reaches the critical level, the filed must be irrigated. In this method, the soil moisture must be measured precisely using soil moisture sensor.

Few researches have been carried out to study the drip irrigation system for sugarcane in the northeast of Thailand, especially to compare the full irrigation with limited irrigation and to compare the efficiency of drip irrigation controlled by the two methods. Therefore, this research aimed to study the effects of the water apply amount and timing of drip irrigation and the effects of drip irrigation controlled by a wireless sensor system and water balance model on growth, physiological process, yield, and yield components of sugarcane.

1.2 Research objectives

1.2.1 To study the effect of drip irrigation controlled by the water balance model with full and half irrigation on growth, yield, and yield components in sugarcane

1.2.2 To study the physiological process of sugarcane in the water deficit condition and well-irrigated conditions

1.2.3 To compare the effect of drip irrigation controlled by a water balance model and a wireless sensor system on growth and yield of sugarcane

CHAPTER II
LITERATURE REVIEW

2.1 The importance of sugarcane and sugarcane production situation

Sugarcane (*Saccharum officinarum* L.) is in a family of Gramineae, the same family as bamboo, grass and grains such as wheat, rice, corn and barley. Zhang et al. (2019) has divided the plants of this genus into 6 species i.e., S. *spontaneum*, S. *robustum*, S. *officinarum*, S. *barberi*, S. *sinense* and S. *edule*.

Currently, Thailand is the second largest exporter of sugar in the world after Brazil. The world's major sugar consumers are India and China. Although Brazil is the largest sugar exporter in the world, delivering sugar to big market (Asian countries) results in high shipping costs that gives Thailand an advantage in terms of transportation costs. High sugar production is also an advantage point that Thai sugar can compete with Brazil.

The Brazilian Ministry of Trade reported that Brazil exported 1.21 million tons of sugar in February 2019 (raw sugar value) increased 10 percent from 1.10 million tons in January 2019 but that decreased 17.69 percent from 1.47 million tons in the same period last year. The Indian Sugar Association reported that in the production season 2018/19, sugar factories have 2.20 million tons of sugar contracts starting on October in 2018. The sugar factories have already delivered more than 1 million tons of white sugar and almost equal raw sugar to Bangladesh, Sri Lanka and Somalia. The Production Management Center, Office of Cane and Sugar Board reported that sugarcane from November 20, 2018 to March 15, 2019 there were 112,570,547 tons of sugarcane harvested into the sugar mill where it produced 9,722,334 tons of raw sugar and 2,530,153 tons of white sugar. The sweetness of sugarcane is 12.47 CCS. Average sugar yield per ton of sugarcane is 108.84 kg per ton (Office of Agricultural Economics, 2019). The major production sites are in the northeast, Nakhon Ratchasima, Udon Thani and Khon Kaen (Office of the Cane and Sugar Board, 2017) In the production year 2016/17, there were 47 provinces of sugarcane cultivation in the survey area of Thailand, with total growing area of 10,988,489 rai.

2.2 Growth of sugarcane

The growth of sugarcane is divided into 4 phases.

2.2.1 Germination phase

It starts from planting until shoots emerge in the soil that will take about 2– 3 weeks, which depends on many factors such as varieties, soil types and environmental conditions. The number of seedlings per rai will determine the production of sugarcane per unit area.

2.2.2 Tillering phase

Tillering will start from 1.5 to 2.5–4 months after planting (MAP). Clumping is a physiological process of repetition under the ground. The factors that affect the tillering number include soil moisture, light, temperature, and fertilizer. When shoots occur in the beginning, they will be strong, but if shoots occur in the end, there will be a chance to die or not fully grow. Controlling water and weeds are very important during the tillering period, and also important for cracking, which can stimulate the number of shoots that will affect the yield of sugarcane.

2.2.3 Stalk elongation phase

This phase will occur from 3–4 MAP until about 7–8 MAP. Sugarcane will increase the length and stalk diameter quickly, and after this phase, its growth will be slow and start to accumulate sugar.

2.2.4 Maturity and ripening phase

This phase has a slower growth rate compared to the other stages. When growth slows down, sugar from leaves produced from photosynthesis is less, and most of sugar is accumulated into stalk. At the beginning of maturing, sugar accumulation will start from the base to the tip. Therefore, the base is sweeter than the tip, the accumulation of sugar will increase accordingly until whole stalk with a similar sweetness (ripen).

2.3 Importance of water to plants

Water is a compound found in up to 3 in 4 of the earth. Most of them are in the salty conditions in the sea and ocean, about 97 percent are polar ice, and about 2 percent are snow. The fresh water along various canals is only about 1 percent. In agriculture, water is very important for plant growth. The water is an important element in various parts of plants and necessary for the physiological processes of plants. In natural conditions, the amount of water contained inside plants is very small compared to the amount of water that is absorbed out of the soil through the plants or that is lost from the transpiration. The conditions in which the water in the plant changes until it falls below an appropriate level, directly affects the physiological processes, growth, yield and quality of product. In addition, water also helps to dissolve minerals nutrient in the soil, so that the roots can absorb nutrient to the various parts of plant, and it also helps the soil to be moist that makes the various processes is normal in plant.

Sugarcane is a high water requirement crop compared to other field crops. Therefore, water is an important factor for the growth and productivity of sugarcane, because it is solvent for plant nutrient that affects yield and quality of sugarcane and can stimulate enzyme activity of seed germination. In the northeast region, there is 80 percent sugarcane planting area without irrigation, main relying on rainfall. Sugarcane cultivation in the northeast is planted mostly in late rainy season because the soil has sufficient moisture for germination. Department of Agriculture (2004) reported that sugarcane needed an average annual rainfall of 1,200–1,500 mm. In 2017, the planting area for sugarcane had an average annual rainfall of 1,452 mm approximately in the northeast (Office of the Cane and Sugar Board, 2018) where the amount of rainfall is deficiency for the growth of sugarcane. Each sugarcane variety has the ability to adapt to different soil types and environments. Sansayawichai et al. (2003) reported that irrigation rate should be 40 percent of the evapotranspiration that had no different effects on yield compared with the full water supply in Satuk soil series. Paisancharoen et al. (2012) reported that an average yield of irrigated ratoon1 Khon Kaen 3 variety, with the highest amount of water about 1,566–1,654 mm per season will be 20.03–

21.07 tons/rai. While the half amount of water supply with 70.08–122.4 mm has a decrease in water use efficiency of 12.2–12.8 kg/rai/mm. Kaushal et al. (2012) reported that sugarcane was a plant that took quite a long time to create biomass. Therefore, it needs about 1,100–2,200 mm of water per season. Drip irrigation for sugarcane can increase water use efficiency 60–200 percent, save up water to 20–60 percent and increase yield and quality by as much as 7–25 percent compared to conventional irrigation. Therefore, the drip irrigation system has been used to increase the yield of sugarcane in agriculture. If sugarcane receives sufficient water throughout the growth period, the yield will be increased. The irrigation rate should be provided at 24 mm. When the evapotranspiration is 40 and 60 mm, the yield is higher than other treatments with 15.9 and 16.1 tons per rai, respectively (Kapetch et al., 2010). There was a comparison between drip irrigation system and double groove system, with sugarcane U Thong 3 variety using the recommended fertilizer application rate (12–6–12) in Kamphaeng Saen soil series, Suphan Buri Province in 2004/05 and 2005/06. It was found that the drip irrigation system was in accordance with the water requirement of plant, and that the water consumption was 1.25 times the water requirement of plant. The sugarcane had higher yield and quality. The average yield of sugarcane with irrigation was 19.75 tons/rai compared to rainfall with 16.13 tons/rai and average the yield of ratoon1 was of 18.69 tons/rai compared to 14.70 tons/rai (Kaewkhongkha et al., 2005).

2.4 Determination of plant water requirement

2.4.1 Water use of crop evapotranspiration (ETc)

Soil moisture can be controlled by water supply in plant roots zone between Permanent Wilting Point (PWP) and Field Capacity (FC) or during the humidity range when the plants absorb water easily. Tungsombun (2006) also reported that plants were able to absorb water easily when soil moisture decreases 50–70%. Soil moisture is allowed to reduction before next water supply that is called Allowable Depletion. Soil moisture content between capillary water and absorbed water after plants absorption is called Critical Point (Figure 2.1).

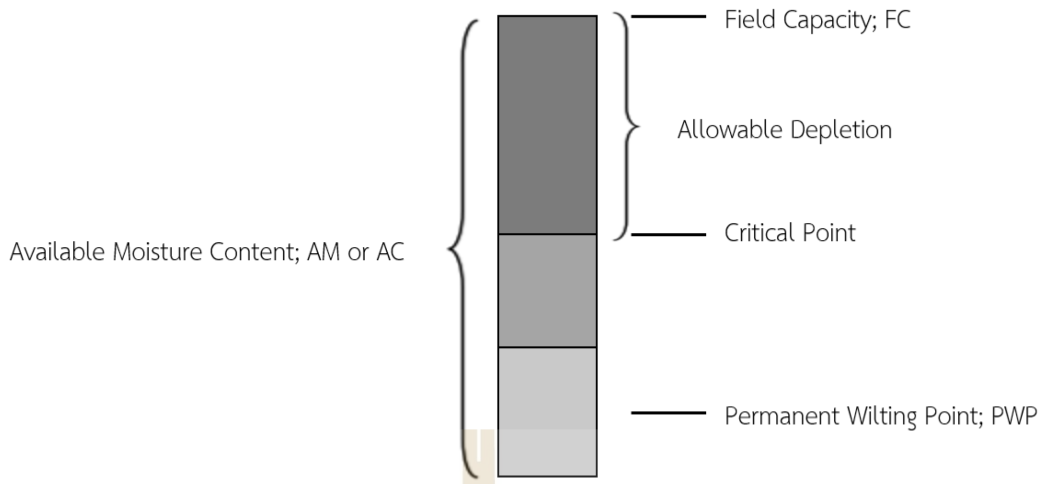

Figure 2.1 The relationship between soil moisture and determination the water of plants (Thongaram et al., 2002).

Generally, the amount of water supply should be according to water requirement of plant and WHC of soil that can be measured by using a device of moisture measuring, which is a sensor that used to measure moisture of different soil layers accurately. Providing water to the plants before soil moisture decreases to the critical point that is required for soil moisture content to back to the FC. If the soil moisture content is lower than the critical point, it will affect the yield and quality of plant. Providing water to plants using the reference crop evapotranspiration can ensure soil moisture content as possible as closing to FC. Currently, there are various types of humidity sensors used for many plants but few used in sugarcane.

Sugarcane requires a lot of water for growth compared to other crops. Water is an important factor for growth and productivity of sugarcane. Providing appropriate irrigation in each growth phase will increase growth and yield of sugarcane. Shoot of sugarcane that is response to irrigation rate will be reduced obviously when the soil moisture is not enough. Kapetch et al. (2010) investigated the response of sugarcane to the water during various growth phases in Satuk soil series and found that the water deficiency in tillering phase caused a decrease in cane number and yield. Sansayawichai & Thanomsap (2006) suggested that water should be supplied precisely in germination phase and stalk elongation phase when there is duration of 170 days.

Determination of crop evapotranspiration using the climatic data is the easiest and most convenient way. Evaporation of surface will depend on properties of surface evaporate of water and climate defined as the evaporative demand. Therefore, the evaporated surface should be standardized, such as water surface or conversion of the plants that use water completely and the area covered. The evaporation of water from such surfaces only depends on climatic factor. Therefore, the climatological data can be used to predict evaporation of water that is calculated by three equations.

1) Evapotranspiration (ETp) and Crop coefficient (Kc), Crop coefficient (Kc) is defined as the ratio between Crop Evapotranspiration (ETc) and potential evapotranspiration (ETp), and the value range is 0-1 that can be changed, according to type of plant, growth period, season, period of year and place. Kc has been collected for each plant in each growth stage, such as rice, sugarcane, vegetables, biennial crops and field crops (Thongaram et al., 2002).

The equation is showed as follows.

$$KC = \frac{ETc}{ETp}$$

The ETc can be calculated from coversion equation.

$$ETc = Kc \times ETp$$

Reference Crop Evapotranspiration or potential evapotranspiration (ETp) is defined as the amount of water loss from the standard crop or reference crop (grass field or alfalfa) that covers the soil all year and obtains enough water all times. The evaporation and transpiration can be affected by external factors, such as blowing the wind to required ETp or depending on climate change solely. In addition to the direct measurements, ETp also can be calculated from the climate at time and place of trial or place that will bring ETp to use in. There was a gathered ETp in the provinces where it is distributed monthly from climate data average 25 year (Thongaram et al., 2002).

2) Crop coefficient (Kc), Class A Pan coefficient (Kp) and Class A Pan Evapotranspiration (Epan) where the value is read directly from equipment installed in the filed plot for plant. The ETc equation is showed as follows.

$$ETc = Kp \times Epan \times Kc$$

Where ETc = Crop Evapotranspiration

Kp = Class A Pan coefficient

Epan = Class A Pan Evapotranspiration

Kc = Crop coefficient

3) Class A Pan Evapotranspiration (Epan) and Class A Pan coefficient (K´p) The ETc equation is showed as follows.

$$ETc = K'p \times Epan \times Kc$$

Where ETc = Crop Evapotranspiration

K´p = Class A Pan coefficient

Epan = Class A Pan Evapotranspiration

Kc = Crop coefficient

ETc calculated from climatic data using ETp and Kc is the most popular method because it can obtain results easily without installing equipment or measuring Epan, but it needs ETp of planting area and Kc value of crop that has been listed in Table 2.1 and Table 2.2.

From the Table 2.1, it is found that the Kc value is low during the first month and increases with sugarcane growth. The value decreases when sugarcane begins to accumulate sugar and stop the growth of stems, indicating that Kc value is depend on the age of the plant. Paisancharoen et al. (2012) found that in the sandy loam soil, Warin soil series, Khon Kaen province, the Kc values of ratoon1 Khon Kaen

3 variety were 0.69, 0.39, 0.84, 2.28 and 0.75 at the Initial phase (0–45 days), Dormancy phase (46–120 days), Tillering phase (121–225 days), Sugar accumulation phase (226–330 days) and Maturity and ripening (331–360 days), respectively. Da Silva et al. (2013) reported that the productivity of sugarcane was increased according to the increasing level of soil available water, and that the yield was 110.2–136.1 tons/ha obtained from the irrigation of 75 and 100% of ETo, respectively.

Table 2.1 The crop coefficient (Kc) value of crop (Royal Irrigation Department, 2011).

Months	Crop coefficient (Kc)						
	Modified Penman	Blaney–Criddle	Pan Method	Thornthwaite	Hargreaves	Radiation	Penman–Monteith
1	0.47	0.56	0.56	0.56	0.60	0.53	0.65
2	0.68	0.83	0.84	0.71	0.83	0.80	0.86
3	0.85	1.04	0.94	0.88	1.00	1.04	1.13
4	1.03	1.28	1.27	1.06	1.16	1.21	1.35
5	1.20	1.54	1.73	1.18	1.35	1.41	1.56
6	1.00	1.17	1.50	1.14	1.19	1.06	1.29
7	0.86	0.98	1.23	0.80	1.16	0.96	1.20
8	0.65	0.68	0.74	0.93	0.88	0.63	0.93
9	0.50	0.57	0.48	0.53	0.55	0.53	0.63
10	0.42	0.53	0.45	0.44	0.48	0.48	0.52
Average	0.76	0.90	0.92	0.82	0.91	0.85	1.01

Table 2.2 Potential evapotranspiration (ETp) of Penman–Monteith monthly in the northeast of Thailand (Royal Irrigation Department, 2011).

Province	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Nong Khai	3.1	3.8	4.6	4.6	4.0	3.6	3.5	3.4	3.5	3.6	3.3	3.0
Loei	3.3	4.1	4.8	5.1	4.4	4.1	3.7	3.6	3.6	3.6	3.2	3.0
– Royal Agricultural Station Loei	3.2	4.0	4.7	4.8	4.2	3.9	3.9	3.4	3.8	3.5	3.4	3.0
Udon Thani	3.3	4.1	4.9	5.2	4.6	4.1	3.7	3.6	3.6	3.7	3.7	3.2
Sakon Nakhon	3.4	4.1	4.9	5.0	4.4	4.0	3.6	3.4	3.9	3.9	3.6	3.3
– Royal Agricultural Station Sakon Nakhon	3.1	3.8	4.5	5.0	4.4	4.3	3.9	3.7	4.0	3.8	3.4	3.1
Nakhon Phanom	3.3	3.9	4.3	4.5	4.0	3.5	3.4	3.3	3.5	3.6	3.6	3.2

Table 2.2 Potential evapotranspiration (ETp) of Penman–Monteith monthly in the northeast of Thailand (Continued) (Royal Irrigation Department, 2011).

Province	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
– Royal Agricultural Station Nakhon Phanom	3.5	4.0	4.5	5.0	4.3	4.3	3.8	3.3	3.8	3.6	3.6	3.3
Khon Kaen	3.7	4.2	5.1	5.0	4.7	4.3	3.9	3.7	3.6	3.8	3.8	3.6
– Royal Agricultural Station Tha Phra	3.2	3.8	4.5	4.8	4.3	3.9	3.9	3.4	3.5	3.6	3.5	3.2
Mukdahan	3.7	4.2	5.0	5.2	4.1	3.6	3.6	3.4	3.6	3.8	4.0	3.5
Mahasarakham	3.6	4.2	4.7	5.2	4.6	4.2	3.8	3.6	3.6	3.8	3.8	3.6
Kalasin	4.2	4.9	5.4	5.5	4.8	4.3	4.2	3.7	3.7	4.1	4.3	4.1
Chaiyaphum	3.6	4.2	5.0	5.1	4.5	4.1	3.8	3.6	3.6	3.8	3.9	3.5
Roi Et	3.5	4.1	4.7	4.8	4.2	3.9	3.8	3.6	3.6	3.6	3.7	3.5
– Royal Agricultural Station Roi Et	4.0	4.4	4.9	5.3	4.6	4.6	4.2	3.9	3.6	3.8	4.1	3.9
Ubon Ratchathani	4.0	4.5	4.9	5.0	4.5	4.0	3.9	3.7	3.4	3.7	4.2	4.2
– Royal Agricultural Station Ubon Ratchathani	3.6	3.7	4.2	4.1	3.7	3.6	3.6	2.9	3.2	3.3	3.6	3.4
Srisaket	–	–	–	–	–	–	–	–	–	–	–	–
– Royal Agricultural Station Srisaket	3.4	3.9	4.6	4.8	4.4	4.4	4.2	3.7	3.9	3.6	3.8	3.5
Nakhon Ratchasima	3.4	4.0	4.4	4.6	4.2	4.0	3.9	3.8	3.4	3.4	3.5	3.4
– Royal Agricultural Station Pak Chong	4.7	4.7	5.0	4.8	4.2	4.5	4.3	4.0	3.4	3.5	4.4	4.5
Chokchai	3.5	4.2	4.7	4.7	4.1	4.2	3.8	3.7	3.3	3.6	3.6	3.4
Surin	3.8	4.4	4.8	4.9	4.2	4.1	3.7	3.6	3.6	3.7	3.8	3.8
– Royal Agricultural Station Surin	3.5	4.0	4.4	4.6	4.0	4.0	3.5	3.5	3.6	3.6	3.7	3.4
Tha Tum	3.5	4.2	4.8	5.0	4.4	4.0	4.0	3.5	3.6	3.7	3.9	3.6
Buriram	4.2	4.8	5.3	5.5	4.7	4.7	4.1	3.7	3.6	3.9	4.1	4.0
Nang Rong	3.6	4.2	4.8	4.9	4.4	4.0	3.9	3.6	3.6	3.8	3.9	3.6

2.4.2 Measuring soil moisture content

In present, there are various methods to measure soil moisture content accurately.

1) Soil water holding capacity (SWHC)

In the northeast of Thailand, most soil textures are loamy sand or sandy loam, with low fertility and SWHC that is affected by chemical, physical and biological properties of soil, which can help the soil to stock up on more nutrients. The water holding capacity in different soil textures has different critical points. Before planting, it is necessary to measure the SWHC and can be achieved by many methods using soil samples, such as gravimetric method and machine pressure plate. The rate of water supply for sugarcane can be calculated by analyzing the value of pressure plate. Different soil textures have different SWHC (Table 2.3 and 2.4).

Table 2.3 Soil water holding capacity in different soil textures (Thongaram et al., 2002).

Texture	Soil water holding capacity (mm water /cm soil)		
	Total	Available	Non-available
Sandy soil	0.65–1.50	0.35–0.85	0.30–0.65
Sandy loam soil	1.50–2.30	0.75–1.15	0.75–1.00
Loam soil	2.30–3.40	1.15–1.70	1.15–1.50
Clay loam soil	3.40–4.00	1.70–2.00	1.70–2.00
Sandy clay loam soil	3.60–4.15	1.50–1.80	2.10–2.35
Clay soil	3.80–4.15	1.50–1.60	2.30–2.55

Table 2.4 The physical properties of the soil related to moisture and available moisture that is between field capacity, permanent welting point (Thongaram et al., 2002).

Soil texture	AS	FC	PWP	Available Moisture		
				Aw (%)	Pv (%)	D (mm/cm soil)
	(1)	(2)	(3)	(4)=(2)-(3)	(5)=(4)x(1)	(6)=(4)x(1) x B/100
1. Sandy	1.65	9	4	5	8	0.8
	(1.55-1.80)	(6-12)	(2-6)	(4-6)	(6-10)	(0.6-1.0)
2. Sandy loam	1.50	14	6	8	12	1.2
	(1.40-1.60)	(10-18)	(4-8)	(6-10)	(9-15)	(0.9-1.5)
3. Loam	1.40	22	10	12	17	1.7
	(1.35-1.50)	(18-26)	(8-12)	(10-14)	(14-20)	(1.4-2.0)
4. Clay loam	1.35	27	13	14	19	1.9
	(1.30-1.40)	(23-31)	(11-15)	(12-16)	(16-22)	(1.6-2.2)
5. Silty clay	1.30	31	15	16	21	2.1
	(1.25-1.35)	(27-35)	(13-17)	(14-18)	(18-23)	(1.8-2.3)
6. Clay	1.25	35	17	18	23	2.3
	(1.20-1.30)	(31-39)	(15-19)	(16-20)	(20-35)	(2.0-3.5)

Note: (1) AS=Apparent Specific Gravity, (2) FC=Field capacity (% dry weight), (3) PWP= Permanent welting point (%Dry weight), (4) Aw=Available Moisture Content (%dry soil weight), (5) Pv=Available Moisture Content (%volume) and (6) D= Available Moisture Content (mm./cm.), B=depth of soil at 10 mm

2) Sensor system

Wireless sensor network (WSN) is a small sensor device used to measure the various properties of the environment, such as temperature, humidity and etc. It can digitize the environment around or respond the environment automatically through data processing. WSN is formed from a combination between embedded system of technology and wireless communications that transmit data between sensor nodes with ad–hoc formats. The highlight of the sensor network is based on the ad–hoc protocol, there is no need to install basic equipment for network as with WLAN or GSM networks.

In addition, the sensor node design is small size and low power consumption, allowing installation in various environments. Sensor network technology is expected a technology in pervasive computing by create an artificial environment. In this experiment, the watermark was chosen. The principle of the sensor is to read the moisture content from matric potential that there is directly related to soil moisture and displayed in kPa unit. If the soil has a lot of water, the soil water potential will be minimum. But when the soil has low moisture, the water potential is high. The sensor is displayed via a mobile phone connected to wireless sensor network. When soil moisture sensor reaches a critical value, the water supply must be returned to field capacity. Wonprasaid et al. (2021) reported that drip irrigation using soil moisture sensor values is a real–time water supply that was accurate and could increase water use efficiency by installing sensors to measure soil moisture at the roots zone of sugarcane at 20 and 30 cm of soil depth. Xie et al. (2020) found that using sensors to control irrigation reduced water by 10-80% compared to irrigation based on the water balance model. Masseroni et al. (2016) found that increasing the irrigation water use efficiency was a key factor for improving irrigation management and designed a system for soil water monitor. Pereira et al. (2020) reported that soil water balance (SWB) modeling with traditional models for real time irrigation scheduling, use of cloud and IoT technologies was developed into applications to the farm practice for precision agriculture.

- Principles and Operational Characteristics of the Watermark Sensor

The Watermark sensors (model 200SS) operate on the same principles as other electrical resistance sensors. Water conditions inside the Watermark sensor change with corresponding variations in water conditions in the surrounding soil. These changes within the sensor are reflected by differences in electrical resistance between two electrodes imbedded in the sensor. Resistance between the electrodes decreases with increasing soil water. In other electrical resistance sensors, plaster of paris, gypsum, glass fibers, ceramic, or nylon cloth has been used as the porous medium between the sensor and the surrounding soil, which is also known as the equilibrium medium. The Watermark is made of a porous ceramic external shell with an internal matrix structure containing two electrodes. In the newer design of the Watermark sensor, the matrix material is surrounded by a synthetic membrane for protection against deterioration and as a contact point with the soil. An internal cylindrical tablet buffers against soil salinity levels that occur in some irrigated soils. A synthetic porous membrane is surrounded by a stainless steel casing or sleeve with holes (Irmak et al., 2016). Watermark sensor will be measure moisture in the form of water potential related to the water use of plants, when the soil draws water with a force of 80 kPa, the plant can bring water to use. But if the soil pulls water with a force that is greater than 80 kPa, the plant will not be able to draw water from (Table 2.5). The advantages of watermark sensor, such as 1) watermark sensor is cheaper and requires less maintenance compared to EC-5 sensor 2) It is a measure of moisture with water pulling force. Making it compatible with all of soil types without having to measure soil moisture. 3) Negligible change in watermark sensor performance with variation in soil temperature. But there is a limitations, such as 1) users must have knowledge and understanding of the principles of watermark sensor so it can be used effectively. 2) It is low accurate in sandy soils because of their larger particle size (Zazueta & Xin, 1994).

Table 2.5 Depletion (in per foot) in available SWHC versus soil matric potential; AWHC; and suggested irrigation trigger points for different soil textures (Irmak et al., 2016).

Soil matric potential (kPa)	Soil type, depletion in inches per foot associated with a given soil matric potential value measured by the Watermark sensors, and available water holding capacity for different soil types							
	Silty clay loam topsoil, Silty clay subsoil (Sharpsburg)	Silt-loam topsoil (Keith)	Upland silt loam topsoil, Silty clay loam subsoil (Hastings, Crete, Holdrege)	Bottom land Silt-loam (Wabash, Hall)	Fine sandy loam	Sandy loam	Loamy sand (O'Neill)	Fine sand (Valentine)
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20	0.00	0.00	0.00	0.00	0.20	0.30	0.30	0.30
33	0.20	0.14	0.00	0.00	0.55	0.50	0.45	0.55
50	0.45	0.36	0.32	0.30	0.80	0.70	0.60	0.70
60	0.50	0.40	0.47	0.44	1.00	0.80	0.70	0.70

Table 2.5 Depletion (in per foot) in available SWHC versus soil matric potential; AWHC; and suggested irrigation trigger points for different soil textures (Continued) (Irmak et al., 2016).

Soil matric potential (kPa)	Soil type, depletion in inches per foot associated with a given soil matric potential value measured by the Watermark sensors, and available water holding capacity for different soil types							
	Silty clay loam topsoil, Silty clay subsoil (Sharps burg)	Silt-loam topsoil (Keith)	Upland silt loam topsoil, Silty clay loam subsoil (Hastings, Crete, Holdrege)	Bottom land Silt-loam (Wabash, Hall)	Fine sandy loam	Sandy loam	Loamy sand (O'Neill)	Fine sand (Valen tine)
70	0.60	0.50	0.59	0.50	1.10	0.80	0.80	0.80
80	0.65	0.55	0.70	0.60	1.20	1.00	0.93	1.00
90	0.70	0.60	0.78	0.70	1.40	1.20	1.04	N/A
100	0.80	0.68	0.85	0.80	1.60	1.40	1.10	N/A
110	0.82	0.72	0.89	0.88	N/A	N/A	N/A	N/A
120	0.85	0.77	0.91	0.94	N/A	N/A	N/A	N/A
130	0.86	0.82	0.94	1.00	N/A	N/A	N/A	N/A
140	0.88	0.85	0.97	1.10	N/A	N/A	N/A	N/A
150	0.90	0.86	1.08	1.20	N/A	N/A	N/A	N/A
200	1.00	0.95	1.20	1.30	N/A	N/A	N/A	N/A
Water holding capacity (in/ft)	1.8-2.0	1.8-2.0	2.20	2.00	1.80	1.40	1.10	1.00
*Suggested range of irrigation trigger point (kPa)	75-80	80-90	90-110	75-80	45-55	30-33	25-30	20-25

(N/A: not applicable), (*)The trigger points were calculated with the assumption of no sensor malfunction.

- Tools for studying soil moisture

Tools for studying soil moisture by measuring some properties of soil that are related to the amount of water, which the popular tools are as follows

1) Gravimetric method is a standard method for soil moisture measurement. The soil samples are oven dried at 105–110°C. The gravimetric soil moisture is calculated by Thongaram et al. (2002) as follows:

$$\text{Moisture (\%weight)} = \frac{\text{Wet weight-Dry weight}}{\text{Dry weight}} \times 100$$

2) Tensiometer is a measure of water potential by measuring tensile of the soil by using a tensiometer embed into the soil in the area that needs to be measured 3–4 days before measuring. This technique is suitable for measuring moisture from saturated to 8.5 bars.

- Principle of Tensiometer

The porous tip will be filled with water. The surface tension of the water that the contact surface between the water and air is a small hole in the gap. The water can flow through this channel that is connected to the water film surrounding the soil particles. When the soil is dry, the water film that surrounds the soil particles is thin and attached to soil particles with greater force. There will be the force to suck the water out of tensiometer through the porous tip causing the water in tensiometer to become more tension and this tension will rise until the water from the inside of tensiometer is stops. The water stress in the soil is equal t0 the tensiometer reading. On the other hand, if the soil is wet (may be due to rainfall or irrigation), the stress of water in the soil will decrease. While the stress of tensiometer is still high, the water will flow from the soil into the tensiometer via a hole in the porous tip. When the water tension in the soil is equal to the tensiometer, the water will stop flowing. The stress of water in the soil at moisture level can be read from the tensiometer as shown in Table 2.6.

Table 2.6 The meaning of value from the tensiometer (Kanchanaprasert et al., 2003).

Readable value	Mean
0	The saturated soil with water, very wet
0–15	Soil moisture is at of field capacity level, suitable moisture for plants that need high moisture.
25	The plants will begin to be water deficit.
>25	The plants are affected by water deficit, the plants grown in pots will begin to show water deficit. Especially, if it is coarse texture soils.
40–50	The root of plants depth 50 cm or more than will begin to water deficit.
70	The root of plants depth 75 cm or more than will begin to water deficit.
80	The plants should be irrigated in any case.

3) Moisture block, this method uses gypsum sticks consisting of two electrodes embed into the soil in the area that needs to be measured. The principle of reducing electrical conductivity when soil moisture decreases is a suitable measure for the moisture content of dry soil ranging from –0.5 to –15 bars. After the embedding of gypsum sticks in the soil about 1 week, the moisture in the gypsum is adjusted to the balance level of the soil. Therefore, measuring by using soil moisture tester and then draw a graph showing the changes in soil moisture compared to the amount of rain each month.

4) Neutron probe, the principle is to release the fast neutron radiation from the probe that is dropped into the ground in various depths. When this fast neutron radiation attaches hydrogen ions of water molecules or soil moisture, it will be changed to slow moving neutrons and reflect to probe. High readings show that there is a high amount of water in the soil. It is a tool that can measure soil moisture quickly and can be continuously measured.

2.5 Irrigation system

Suitable irrigation systems in an area are depended on many factors such as soil type, slope, cost, availability of water, availability of labor, and machine tools. Current irrigation systems that are used both in Thailand and abroad as follows.

2.5.1 Furrow irrigation

Furrow irrigation is an irrigation system that is widely used both in Thailand and abroad. Because it is a low–cost system, convenient and easy to practice but there are restrictions on the sugarcane plantation plot to be relatively smooth with a slope of not more than 3 percent. The efficiency of the irrigation will vary between 30–90 percent and increase efficiency providing water correct and proper management.

2.5.2 Sprinkler irrigation

This type of irrigation is applicable to all areas and all types of soil. Efficient use of water may exceed 75 percent if correct and proper management in provided. There are many types of water supply, such as a big springer that use a high–pressure water pump.

2.5.3 Drip irrigation

Drip irrigation is a method of providing high efficiency water used for planting almost all plants. The principle of drip irrigation is to apply water to the soil in the form of a cutting cone and allow the plant roots to grow within cone of moisture by maintaining the moisture in soil to be in field capacity all times. It can be applied in many types of plants. This method is popular, especially in situations that face water and labor shortage. There are 2 types of drip irrigation use in sugarcane fields.

1) Surface system, this system will place a drip tape or pipe on surface of the ground in the center of beside groove.

2) Subsurface system, the drip line will be install under subsoil surface before planting. Usually the buried depths are about 25–30 cm or under sugarcane stalk about 10 cm.

There are many advantages of drip irrigation systems such as 1) High water efficiency when compared to other methods 2) Suitable all types of area and soil, whether loam, sandy or clayey soils 3) Can be used with various types of plants, except plants that need water flooding 4) Suitable for water shortage areas or need to use water economically 5) Helps the plant have more roots and increase water and nutrients use efficiency (Raj et al., 2013) 6) Use less labor to apply water and can provide fertilizer and other chemicals such as pesticides along with water system. Fertilization via irrigation system can increase efficiency of fertilizer use of plants more than 80-90% (Thompson et al., 2003) 7) Controlling amount of water and fertilizer to even amount that the required by plants.

Limitations of drip systems such as 1) The equipment has a high price, complex mechanism, need high skill and knowledge and understanding of various equipment and maintenance 2) If the water is not clean, it will clog easily 3) Insects or biting animals damage.

CHAPTER III
MATERIALS AND METHODS

3.1 Research Methodology

A series of 3 experiments were conducted during 2018 – 2020. The 1st experiment aimed to study the effect of drip irrigation controlled by the water balance model on growth, yield, and yield components in sugarcane. While the 2nd experiment was conducted under greenhouse conditions, it aimed to study the physiological process of sugarcane in the water deficit condition and well–irrigated conditions and the 3rd experiment aimed to compare the effect of drip irrigation controlled by a water balance model and a wireless sensor system on growth and yield of sugarcane.

3.2 Experiment 1: Controlling drip irrigation for sugarcane by water balance model.

3.2.1 Experimental design

The experimental design was a randomized complete block design (RCBD) with 3 treatments and 3 replications. Sugarcane CV. Khon Kaen 3 (KK3) was planted in SL soil at KI sugarcane field, Buachet, Surin, Thailand (14°31'19.0"N 103°54'27.2"E).

Sugarcane CV. KK3 is a popular cultivar in the Northeast. It is a hybrid between clones 85-2-356 and K 84-200. The average cane yield is 12-22 tons/rai. It is fast growing with high ratooning ability. The recommended planting area is flat or upland with good drainage. It is suitable for planting in sandy loam soil (Office of Cane and Sugar Board, n.d.).

The treatments were as follows:

T1: Control (rainfed practice)

T2: Half water supply based on the water balance model

T3: Full water supply based on the water balance model

3.2.2 Materials and Method

1) Soil preparation and planting

The soil was prepared by deep plowing and turning over to control weeds. About a week after deep plowing, the soil was rotary plowed. The sugarcane was planted with the growing machine at the distance between double rows of 1.6 m. The plot size of each treatment was 70x33.6 m.

2) Soil properties before the experiment

The soil was analyzed for soil fertility, which was used to determine the fertilizer formula. The acidity–alkalinity (pH) was measured using soil: water (1:1) by pH meter. The electrical conductivity (EC) was measured using soil: water (1:5) by EC Meter. Organic matter (OM) content was analyzed by Walkley and Black method (Walkley, 1945). Available phosphorus was analyzed by the Bray II method (Bray & Kurtz, 1945) and measured by Spectrophotometer. The soil was extracted with 1.0 M of NH_4OAC and exchangeable K, Ca and Mg were measured by Atomic Absorption Spectrophotometer (AAS) (David,1960). The results of soil analysis at the depth of 0–40 cm are shown in Table 3.1. It was found that the soil texture was sandy loam.

Table 3.1 Soil properties before the experiment on CV. KK3.

Sample (dept.)	pH 1:1	EC (dS/m)	OM (%)	Av.P (mg/kg)	Ex.K (mg/kg)	Ex.Ca (mg/kg)
0–40 cm.	4.89	0.138	0.45	17.3	43.3	283

OM: organic matter; Av.P: available P; Ex.K: exchangeable K; Ex.Ca: exchangeable Ca

3) Irrigation management and fertilizer application

3.1) Irrigation management

For all treatments, the water was irrigated to the sugarcane by drip irrigation systems. The drip tapes with the distance among the drip hole of 30 cm and the flow rate of 2 liters/hour were installed at planting. Water was irrigated based on the water balance model equation (1) (Pereira et al., 2020)

$$I=ET+DR+RO+\Delta W-P \qquad (1)$$

When I is the irrigation

ETc is the evapotranspiration

DR is drainage

RO is the surface runoff

ΔW is the AWHC

P is the precipitation

The treatment was irrigated as follows:

– In T1, water was irrigated 2–3 times to maintain the sugarcane germination until 30 days after planting (DAP).

– In T3, water supply was determined from the water balance model using crop water requirement (ETc) and soil water holding capacity (SWHC). The crop water requirement was calculated from historical weather data in the area and crop coefficient (Kc). The amount of water supply each time was based on the field capacity (FC) of the soil. In the 1–2 months after planting (MAP), the available water holding capacity (AWHC) was calculated at a depth of 0–20 cm after 2 MAP, it was calculated at a depth of 0–40 cm The irrigation was supplied when 60 percent of available water was used by sugarcane. If there was rainfall between the irrigation periods, the irrigation was canceled or delayed according to the amount of rainfall (Table 3.2).

– In T2, the water was supplied at the same frequency as full water supply, but the amount of water supply was equal to half amount of water supply in T3.

Table 3.2 The amount of water requirement for sugarcane from January to December 2018 at Bua Chet Farm.

Months	Number of days	ETp (mm/day)	Kc	ETc (mm/day)	ETc (mm/months)	Rainfall (mm)
Jan	31	3.66	0.47	1.72	53.3	5.00
Feb	28	4.31	0.68	2.93	87.9	0
Mar	31	4.89	0.85	4.16	129	90.0
Apr	30	5.10	1.03	5.25	158	45.0
May	31	4.87	1.20	5.84	181	155
Jun	30	4.35	1.00	4.35	135	28.0
Jul	31	4.25	0.86	3.66	110	165
Aug	31	4.08	0.65	2.65	82.2	156
Sep	30	3.79	0.50	1.90	56.9	–
Oct	31	3.84	0.42	1.61	50.0	–
Nov	30	3.71	–	–	–	–
Dec	31	3.53	–	–	–	–
Total (mm)		50.4	7.66	34.07	1,043	644

3.2 Fertilizer application

The fertilizer rates of the nutrient balance model were calculated based on the nutrient balance equation (2) as the same study of Wonprasaid et al. (2021)

$$NS=\frac{NR-(SAN-SM)}{NUE} \qquad (2)$$

Where NS is the nutrient supply (kg/rai)

NR is the nutrient required for the target yield of 20-25 tons/rai

SAN is the amount of soil available nutrients that obtain from soil analysis (kg/rai) in Table 3.3 and 3.7

SM is the minimum amount of soil nutrient (OM=1%, P=10mg/kg and K=60mg/kg for SCL; OM=0.5%, P=5mg/kg and K=30mg/kg for LS and SL)

NUE is nutrient use efficiency for soil uptake (N=80%, P=60% and K=80%) for both soils

The fertilizer rate was based on soil analysis as follows:

– In T1 and T2, fertilizer application was soil applications, urea (46–0–0) was used as the source of N fertilizer, diammonium phosphate (18–46–0) was used as the source of P, and potassium chloride (0–0–60) was used as the K source. The soil fertilizer application was applied 2 times at 1 and 3 MAP in Table 3.3.

– In T3, fertilizers were applied by fertigation using Urea (46–0–0) as the source of N fertilizer, and Monoammonium phosphate (12–61–0) as the source of P, and potassium chloride (0–0–60) as K source. The fertigation was applied every 7–10 days for 7 times from 1 MAP (applied) in Table 3.3. The fertilizers were applied as the same formulas as T1 and T2, but the source of fertilizers was different.

Table 3.3 Rate of fertilizer recommended based on nutrient balance model in SL soil.

Soil texture	N (kg/rai)	P_2O_5 (kg/rai)	K_2O (kg/rai)
SL	22	12	35

3.2.3 Data collection

1) Sugarcane growth parameters

Sugarcane growth parameters were collected at the 2, 4, and 6 MAP in the area of 4.8 x 4 m (19.2 m^2) from recommended double rows (Hassan et al., 2017).

– The plant height was measured from the ground to the top visible dewlap (TVD).

– The shoot number was counted.

– The SPAD chlorophyll meter reading (SCMR) was measured on the 3rd fully expanded leaf from the top of the main stem of each plant at the 4 MAP.

– The plant nutrient of leaf on the 3rd leaf was analyzed at 4 MAP, including N, P, K and Ca.

2) Yield and yield components

The yield and yield components were collected in the area of 4.8 x 4 m (19.2 m^2). The data were collected as follows:

– The stalk length (cm) was measured from the base of the plant to the TVD from 10 stalk samples.

– The stalk diameter (middle of stalk) was measured using a vernier caliper from 10 plant samples.

– The stalk weight (kg/stalk) was randomly measured from 10 plant samples.

– The number of millable cane (NMC) was calculated from recommended area.

– The yield was evaluated in the sampling area and converted into tons/rai.

3.2.4 Statistical analysis

The data of plant growth, yield, and yield components were analyzed using the Statistical Package for the Social Science (SPSS) version 16.0, and the mean comparisons were compared by the Duncan's New Multiple Range Test (DMRT) at P=0.05.

3.3 Experiment 2: Growth and physiology study of Khon Kaen 3 sugarcane cultivated under irrigated and water deficit conditions.

3.3.1 Experimental design

The experiment was conducted in greenhouse conditions at Suranaree University of Technology farm, Muang, Nakhon Ratchasima, Thailand (14°52'38.4"N 102°00'23.0"E). The experimental design was a RCBD with 3 treatments and 3 replications.

The treatments were as follows:

T1: Irrigation (Control)

T2: Water deficit condition at 3 months

T3: Water deficit condition at 7 months

3.3.2 Materials and Method

1) Soil preparation and planting

Sugarcane CV. KK3 was grown in 150–liter pots filled with sandy clay loam soil.

2) Irrigation management

For all treatments, water was supplied to the sugarcane using a drip irrigation system with a flow rate of 8 liters/hour. Irrigation in each treatment was performed as follows:

– In T1, the water supply pattern (frequency and amount) was determined from the water balance model using ETc and SWHC. The ETc was calculated from historical weather conditions in each area and Kc. The number of water supplies each time was based on the FC of the soil. In the 1–2 MAP, the AWHC was calculated at a depth of 0–20 cm. after 2 MAP, it was calculated at a depth of 0–40 cm. The irrigation was supplied when 60 percent of available water was used by sugarcane.

– In T2, the water was supplied as same as T1 until at 3 MAP, after that, no water was irrigated for 14 day to create the water deficit conditions. Then the water was irrigated again until harvesting.

– In T3, the water was supplied as same as T1 until at 7 MAP, after that, no water was irrigated for 16 day to create the water deficit conditions. Then the water was irrigated again until the harvesting.

3.3.3 Data collection

1) Growth parameter

Growth parameter was collected at 3 and 7 MAP.

– The plant height was measured randomly from the soil base to the TVD.

– The shoot number was counted in the pot plant of all treatments.

– The number of leaves was counted in the pot plant of all treatments.

2) Physiological process

– The SCMR was measured on the 3^{rd} leaf using a Chlorophyll Meter (SPAD) at the 3 and 7 MAP.

– The leaf water potential (the 3^{rd} leaf) was measured from 10.00–14.00 hrs (Jaiphong et al., 2017) using a photosynthesis LCi–SD model at 3 and 7 MAP.

– The photosynthetic rate, transpiration rate, and stomatal conductance (the 3^{rd} leaf) were measured from 10.00–14.00 hrs (Jaiphong et al., 2017) using a photosynthesis LCi–SD model at 3 and 7 MAP.

3) Yield and yield components

– The stalk length (cm) was measured from the base of the plant to the TVD in the pot plant of all treatments.

– The stalk diameter (middle of stalk) was measured on the main stalk using a vernier caliper in the pot plant of all treatments.

– The stalk weight (kg) was recorded from the stalk per pot of all treatments.

– The stalk number (stalk/pot) was counted in the stalk per pot plant of all treatments.

– The yield (kg) was recorded from stalk per pot of all treatments.

– The total soluble solid (TSS) (^{o}Brix) was analyzed using reflectometer.

3.3.4 Statistical analysis

The data of growth parameters, physiological process, yield, and yield components were analyzed using the SPSS version 16.0. The mean was compared by the DMRT at P=0.05.

3.4 Experiment 3: Controlling drip irrigation for sugarcane by the wireless sensor system.

3.4.1 Experimental design

The experimental design was a RCBD with 4 treatments and 3 replications. The experiment was conducted on sugarcane CV. KK3, and it was grown in 2 soil textures.

– The Sandy clay loam soil (SCL) was conducted at Suranaree University of Technology farm, Muang, Nakhon Ratchasima, Thailand at the position of 14°52'38.4"N 102°00'23.0"E.

– The Loamy sand soil (LS) was conducted at KI sugarcane field, Buachet, Surin, Thailand, at the position of 14°30'45.0"N 103°54'19.4"E.

In both soils, the treatments were:

T1: Control (no irrigation) + Soil fertilizer application

T2: Drip irrigation controlled by water balance model + Soil fertilizer

T3: Drip irrigation controlled by water balance model + Fertigation

T4: Drip irrigation system controlled by sensor + Fertigation

3.4.2 Materials and Method

1) Soil preparation and planting

Soil preparation and planting were the same as in experiment 1.

2) Soil properties before the experiment in SCL and LS soil

Soil properties before the experiment at a depth of 0–40 cm were analyzed as the same procedure as experiment 1.

The soil at Suranaree University of Technology farm was classified as SCL soil and at KI sugarcane field was classified as LS soil. Soil's chemical and physical properties are shown in Table 3.4.

Table 3.4 Soil properties before the experiment in SCL and LS soil.

Soil properties	SCL soil	LS soil
Chemical properties		
EC (dS/m)	0.070	0.027
pH (1:5)	7.46	5.70
OM (%)	1.25	0.93
Av.P (mg/kg)	8.86	5.03
Ex.K (mg/kg)	76.8	43.7
Ex.Ca (mg/kg)	2,327	650
Ex.Mg (mg/kg)	171	124
Physical properties		
Sand (%)	46.2	81.5
Silt (%)	22.5	9.20
Clay (%)	32.3	9.30
Bulk density (g/cm^3)	1.25	1.35
FC (%v)	36.8	17.9
PWP (%v)	20.3	6.90
AWHC (mm/cm)	1.65	1.10
Texture	Sandy clay loam	Loamy sand

EC: Electrical conductivity; OM: Organic matter; P: Available P; K: Exchangeable K; Ca: Exchangeable Ca; Mg: Exchangeable Mg; AWHC: available water holding capacity; SCL: Sandy clay loam; LS: Loamy sand

3) Irrigation and fertilizer application

3.1) Irrigation

For all treatments, the water was irrigated to the sugarcane using a drip irrigation system (drip tape) which was installed after planting. The distance among the drip hole was 30 cm and the flow rate was 2 liters/hour. The treatment was irrigated as follows:

– T1 was irrigated only 2–3 times after planting until 30 DAP for uniform germination of sugarcane.

– In T2 and T3, the water supply pattern (frequency and amount) was determined from the water balance model using ETc and SWHC in Tables 3.5 and 3.6. The crop water requirement was calculated from historical weather conditions in each area and Kc. The amount of water supply each time was based on the FC of the soil. In the 1–2 MAP, the AWHC was calculated at a depth of 0–20 cm, after 2 MAP, it was calculated at a depth of 0–40 cm. The irrigation was supplied when 60 percent of available water was used by sugarcane. If there was rainfall between the irrigation periods, the irrigation was canceled or delayed according to the amount of rainfall.

– In T4, the soil moisture sensor (watermark) was installed at the soil depth of 20 and 40 cm to monitor soil water potential. When the soil water potential was higher than -80 centibar, water was supplied. At 1–2 MAP, only the soil moisture values of the upper sensor were used, but after 2 MAP the average values of both sensors were used. The amount of water supply each time was based on the FC of the soil.

Table 3.5 The amount of water requirement of sugarcane from February 2019 to January 2020 in SCL soil.

Months	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Total (mm)
Number of days	28	31	30	31	30	31	31	30	30	30	–	–	
ETp	3.95	4.39	4.64	4.20	3.95	3.89	3.79	3.36	3.42	3.51	3.41	3.37	
Kc	0.65	0.86	1.13	1.35	1.56	1.29	1.20	0.93	0.63	0.52	–	–	10.1
ETc (mm/day)	2.57	3.78	5.24	5.67	6.16	5.02	4.55	3.12	2.15	1.83	–	–	4.01
ETc (mm/months)	35.9	117	157	176	185	156	141	93.7	64.6	54.8	–	–	1181

Table 3.6 The amount of water requirement of sugarcane from December 2018 to November 2019 in LS soil.

Months	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Total (mm)
Number of days	31	31	28	31	30	31	30	31	31	30	–	–	
ETp	3.65	3.85	4.96	5.22	5.39	4.83	4.56	4.36	4.04	4.13	4.06	3.97	
Kc	0.65	0.86	1.13	1.35	1.56	1.29	1.20	0.93	0.63	0.52	–	–	10.1
ETc (mm/day)	2.37	3.31	5.60	7.05	8.41	6.23	5.47	4.05	2.55	2.15	–	–	4.72
ETc (mm/months)	73.5	103	157	219	252	193	164	126	78.9	64.4	–	–	1431

3.2) Fertilizer application

The fertilizer rate was based on soil analysis and fertilizer methods were as follows:

– Fertilization in T1 and T2 were soil fertilizer applications in which fertilizers were applied 2 times at 1 and 3 MAP using N (46–0–0), P (18–46–0), and K (0–0–60) in Table 3.7.

– T3 and T4 were fertigations using N (46–0–0), P (12–61–0), and K (0–0–60). For the fertigation, fertilizers were equally applied 7 times from 1 MAP (applied every 7–10 days) in Table 3.7. The fertilizers were applied as the same formulas as T1 and T2, but the sources of fertilizer were different.

Table 3.7 Rate of fertilizer recommended based on nutrient balance model in SCL and LS soil.

Soil texture	N (kg/rai)	P_2O_5 (kg/rai)	K_2O (kg/rai)
SCL	21	16	15
LS	22	16	35

3.4.3 Data collection

1) Rainfall, water requirement, and water supply

Rainfall, water requirement, and water supply were recorded in each treatment throughout the growing season.

Soil water potential was measured at 09:00 am using soil moisture sensors (Watermark), that were installed in the field at 2 soil depths (20 cm and 40 cm).

2) Sugarcane growth

Plant growth was collected at the 2, 4, and 6 MAP in the area of 4.8 x 4 m (19.2 m^2) from recommended double rows.

– The plant height was measured randomly from the soil base to the TVD.

– The shot number was counted.

– The SCMR was measured at the 3rd leaf using a SPAD Meter at the 4 and 6 MAP.

– The nutrient of leaves at the 3rd leaf was analyzed at the 4 MAP, including N, P, K, Ca, and Mg.

3) Yield and yield components

The yield and yield components were collected in the area of 4.8 x 4 m (19.2 m^2), the data were collected as follows:

– The stalk length (cm) was measured from the base of the plant to the TVD from 10 plant samples.

– The diameter (middle of stalk) was measured by using a vernier caliper from 10 plant samples.

– The stalk weight (kg/stalk) was measured from 10 plant samples.

– The NMC was calculated from recommended area.

– The yield was evaluated in the sampling area and converted into tons/rai

– The sugarcane TSS (°Brix) was analyzed using reflectometer.

4) Irrigation Water and Fertilizer use efficiency

Irrigation water use efficiency (IWUE) and Fertilizer use efficiency (FUE) were calculated during the harvesting (Xie et al., 2018) and estimated as follows:

$$\text{IWUE} = \frac{\text{yield (kg/rai)}}{\text{amount of water supply (m}^3\text{/rai)}}$$

$$\text{FUE} = \frac{\text{yield (kg/rai)}}{\text{amount of fertilizer (kg/rai)}}$$

3.4.4 Statistical analysis

The data of plant growth, physiological data, yield, and yield components were analyzed using the SPSS version 16.0, and the mean was compared by the DMRT at P=0.05.

CHAPTER IV
RESULTS AND DISCUSSION

4.1 Experiment 1: Controlling drip irrigation for sugarcane by water balance model.

4.1.1 Sugarcane growth parameter

4.1.1.1 Plant height

It was found that the plant height at 2 MAP was significantly different among the treatments, in contrast, the treatments did not significantly affect plant height at 4 and 6 MAP. At 2 MAP, full irrigation controlled by water balance model (T3) produced the highest plant height (18.8 cm) while the lowest plant height was found in rainfed conditions (T1) (15.4 cm). In addition, T3 tended to produce the highest plant height at 4 and 6 MAP (Table 4.1).

Table 4.1 Effects of irrigation methods on plant height.

Treatment	Plant height (cm)		
	2 MAP	4 MAP	6 MAP
T1: Control (rainfed conditions)	15.4[b]	47.7	151
T2: Half water supply	16.6[b]	53.7	160
T3: Full water supply	18.8[a]	55.1	163
F-test	**	ns	ns
CV (%)	3.39	8.34	2.95

[1] Means in the same columns with different letters are significant differences based on DMRT at $P < 0.05$.

4.1.1.2 Shoot number

The results of shoot number are shown in Table 4.2, shoot number was not significantly different among the treatments at all months (2, 4, and 6 MAP). However, drip irrigation treatments (T2 and T3) tended to produce higher shoot numbers than in rainfed conditions.

Table 4.2 Effects of irrigation methods on shoot number.

Treatment	Shoot number (No./rai)		
	2 MAP	4 MAP	6 MAP
T1: Control (rainfed conditions)	17,627	36,267	17,320
T2: Half water supply	19,596	37,156	17,504
T3: Full water supply	20,933	42,489	17,877
F-test	ns	ns	ns
CV (%)	19.7	15.7	6.81

[1] Means in the same columns with different letters are significant differences based on DMRT at P < 0.05.

4.1.2 SPAD chlorophyll meter reading (SCMR)

Table 4.3 shows the SCMR, it was significantly different among treatments at 4 and 6 MAP. The SCMR was the highest at both MAP in T3 (39.1 and 42.0, respectively), while T1 produced the lowest SCMR at both MAP (36.0 and 38.1, respectively).

Table 4.3 Effects of irrigation methods on SCMR.

Treatment	SCMR (SPAD unit)	
	4 MAP	6 MAP
T1: Control (rainfed conditions)	36.0[b]	38.1[b]
T2: Half water supply	38.8[a]	38.6[b]
T3: Full water supply	39.1[a]	42.0[a]
F-test	*	*
CV (%)	2.52	2.63

[1] Means in the same columns with different letters are significant differences based on DMRT at P < 0.05.

4.1.3 Leaf nutrients analysis

The leaf nutrient analysis showed that leaf nitrogen was significantly different but phosphorus, potassium, and calcium were not significantly different between treatments. The highest nitrogen was found in T3 (1.82%) while the lowest was in T1. P, K, and Ca in irrigation treatments (T2 and T3) tended to be higher than in the rainfed practice.

In the comparison of the leaf analysis and the standard nutrient content, it was found that N and K in all treatments were lower than the standard nutrient content and P was comparable to the standard value. For Ca content, T3 was comparable but T1 and T2 were lower than the standard value (Table 4.4).

Table 4.4 Effects of irrigation methods on plant nutrients of leaf.

Treatment	N (%)	P (%)	K (%)	Ca (%)
T1: Control (rainfed conditions)	1.69^{bc}	0.22	0.80	0.17
T2: Half water supply	1.75^{ab}	0.24	0.80	0.20
T3: Full water supply	1.82^{a}	0.26	0.97	0.26
F-test	**	ns	ns	ns
CV (%)	3.20	19.6	15.6	29.4
Suitable nutrient content in sugarcane leaves	2.00-2.60	0.22-0.30	1.00-1.60	0.22-0.45

[1] Means in the same columns with different letters are significant differences based on DMRT at P < 0.05.

4.1.4 Yield and Yield components

The treatments significantly affected yield and stalk length, but not significantly different stalk diameter, and stalk weight. The highest yield was found in T3 (19.7 tons/ rai) while T1 produced the lowest yield (15.0 tons/ rai). The stalk length was the highest in T3 and lowest in T1 (296 and 260 cm, respectively.). The stalk diameter, stalk weight, and the number of millable canes (NMC) were not significantly different among treatments, but drip irrigation treatments (T2 and T3) tended to produce higher than those in rainfed conditions (T1).

Table 4.5 Effects of irrigation methods on cane yield.

Treatment	Yield (tons/rai)	Stalk length (cm)	Stalk diameter (cm)	Stalk weight (kg/stalk)	NMC (stalk/ rai)
T1: Control (rainfed conditions)	15.0^{b}	240^{b}	2.63	1.24	12,778
T2: Half water supply	16.5^{ab}	262^{b}	2.69	1.29	13,111
T3: Full water supply	19.7^{a}	296^{a}	2.73	1.35	14,444
F-test	*	**	ns	ns	ns
CV (%)	8.68	3.78	3.28	5.75	13.9

[1] Means in the same columns with different letters are significant differences based on DMRT at P < 0.05.

This experiment was conducted to compare the effects of 2 drip irrigation methods (half water supply and full water supply) and rainfed conditions on sugarcane. Both irrigation methods resulted in the improvement of sugarcane growth. The significant difference of plant height occurred between treatments at 2 MAP i.e., the rainfed treatment had the lowest plant height. Less significant differences were observed at 4 and 6 MAP, however, fully water supply still produced the highest plant height while rainfed conditions produced the lowest. Normally, in the northeast conditions, the first period of sugarcane planting is in the period of low rainfall which rainfed sugarcane always faces severe water limitation. The drip irrigation can provide water to meet sugarcane requirement during this period and enhances plant height. The next 4-6 MAP, the rainy season starts, causing the plants in the rainfed treatment to begin to recover from the water deficit but could not reach it's potential. The results were similar to Kapetch et al. (2010) and Khonghintaisong et al. (2017) who reported that when sugarcane experienced drought in early period, plant height significantly decreased and when the rain was recovered to normal conditions in later growth period, the sugarcane partially recovered. Both drip irrigation treatments also produced higher shoot numbers than the rainfed treatment. Similar result was reported by Paisancharoen et al. (2012) who showed that irrigation increased the shoot number at the average of 9,718-12,128 stalk/rai. The plant height and shoot number are important growth characters to predict the sugarcane yield that can be produced.

Beside plant height and shoot number, the SCMR and leaf N content also responded to irrigation. The results showed that full water supply had the highest SCMR and nitrogen content. According to Denise et al. (1995) report, it is a possible role in using a SPAD meter to estimate foliar N status in the field. In other words, the SCMR is high, it indicates that the sugarcane has a high nitrogen content. Peng et al. (1995) reported that the SCMR in plant leaves was an indicator of increased chlorophyll concentrations and higher levels of nitrogen fertilization resulted in higher SCMR values. Siriyoot & Jongkaewwattana (2011) reported that the increase in SCMR resulted in increased biomass dry weight and productivity. From the experiment results and previous reports, it can be implied that well irrigation can enhance N uptake resulting to increased chlorophyll content and consequently enhance growth and productivity.

The sugarcane yield and yield components were different among the irrigation methods. Fully water supply (T3) produced the highest stalk length, stalk diameter, stalk weight, NMC and yield while control treatment produced the lowest of all parameters. The results were similar to other studies such as Wonprasaid et al. (2021) who found that drip irrigation produced higher yield (17.8-22.3 tons/rai) than the rainfed condition (14.9 tons/rai). Paisancharoen et al. (2012) reported that full irrigation can yield 1st ratoon cane of CV. KK3 in an average of 20.0-21.1 tons/rai and Suphakarn et al. (2012) also reported that sugarcane CV. KK3 had a high stalk length (286 cm) under irrigation. Kruangpatee et al. (2017) showed that sugarcane yield was related to four yield components i.e., NMC, stalk weight, stalk length, and stalk diameter. In comparison of the irrigation methods between full water supply (T3) and half water supply (T2), it was found that full water supply could increase sugarcane yield more than half water supply. For half water supply, sugarcane received water only half amount of the full water supply, it is still insufficient water to meet the demand, therefore it’s growth and yield was lower than it’s potential. The results were similar to other studies. Thanomsub & Sansayawichai (2009) reported that the irrigation application at evapotranspiration (E) 60 mm produced the highest yield of 17.2 tons/rai while E 120 mm produced yield of only 13.9 tons/rai. In their study, at E 60 mm and E 120 mm, the irrigation was applied 20 and 10 times respectively throughout the growing season. Puengpa & Boontham (2012) reported that sugarcane growth and yields were positively correlated with the appropriate amount of watering of sugarcane. Even though half water supply produced lower yield than full water supply, it still can be recommended to farmers who have limited amount of reserved water as it still produced high and reliable yield compared to rainfed sugarcane.

4.2 Experiment 2: Growth and physiology study of Khon Kaen 3 sugarcane cultivated under irrigated and water deficit conditions.

4.2.1 Growth parameter

4.2.1.1 Plant height

The result showed that at stress period 1, the water deficit conditions at 3 months (T2) produced the lowest plant height, while the non-stress treatments (T1 and T3) produced similar plant height (Figure 4.1). At stress period 2, T2 still had lower plant height than irrigation treatment (T1), and the water deficit condition at 7 months (T3).

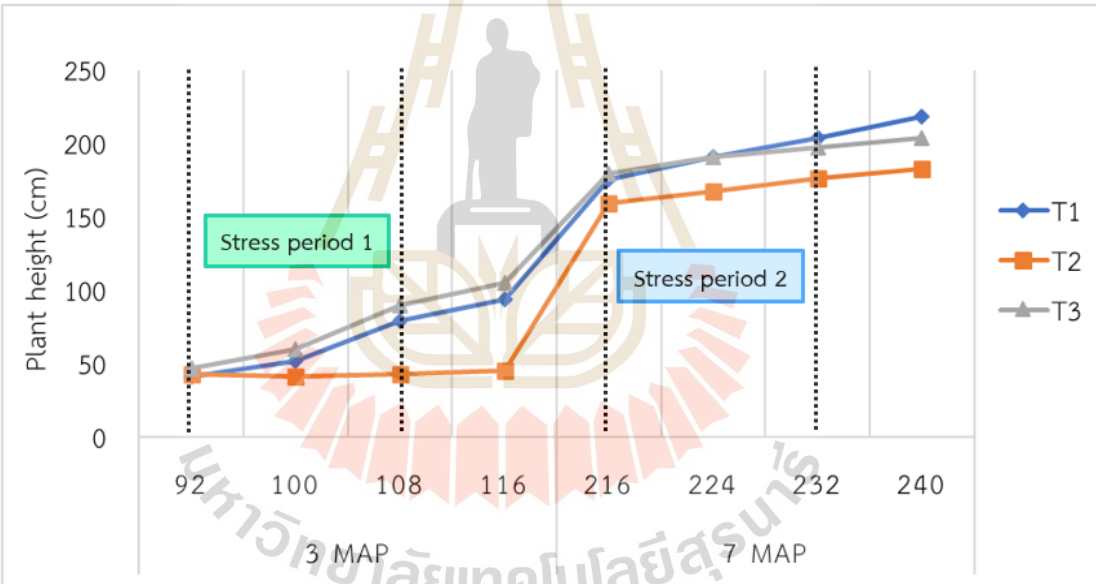

Figure 4.1 Effects of irrigation methods on plant height.

4.2.1.2 Shoot number

The results of shoot number are shown in Figure 4.2. During stress period 1, T2 tended to produce higher shoot numbers than irrigation treatment (T1) and the water deficit conditions at 7 months (T3). In contrast, irrigation treatment (T1) tended to produce higher shoot numbers than water deficit treatments (T2 and T3) during stress period 2.

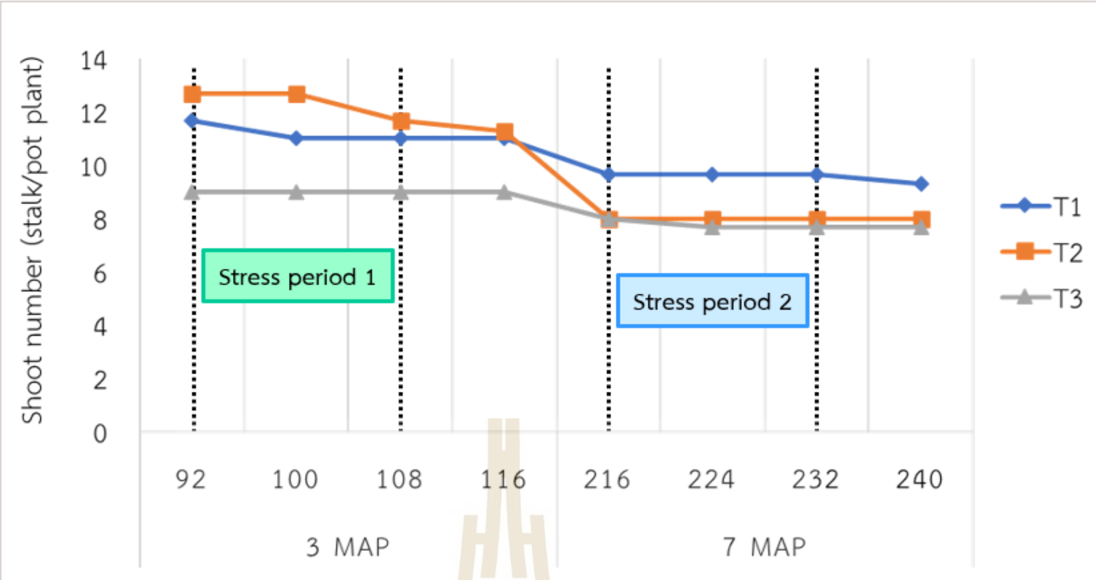

Figure 4.2 Effects of irrigation methods on shoot number.

4.2.1.3 Number of leaves

During stress period 1, irrigation treatment (T1) tended to produce a higher number of leaves, while the lowest number of leaves was found in T2. In contrast, in stress period 2 water deficit (T3) tended to produce the lowest number of leaves, while the irrigation treatments (T1) produced the highest number (Figure 4.3).

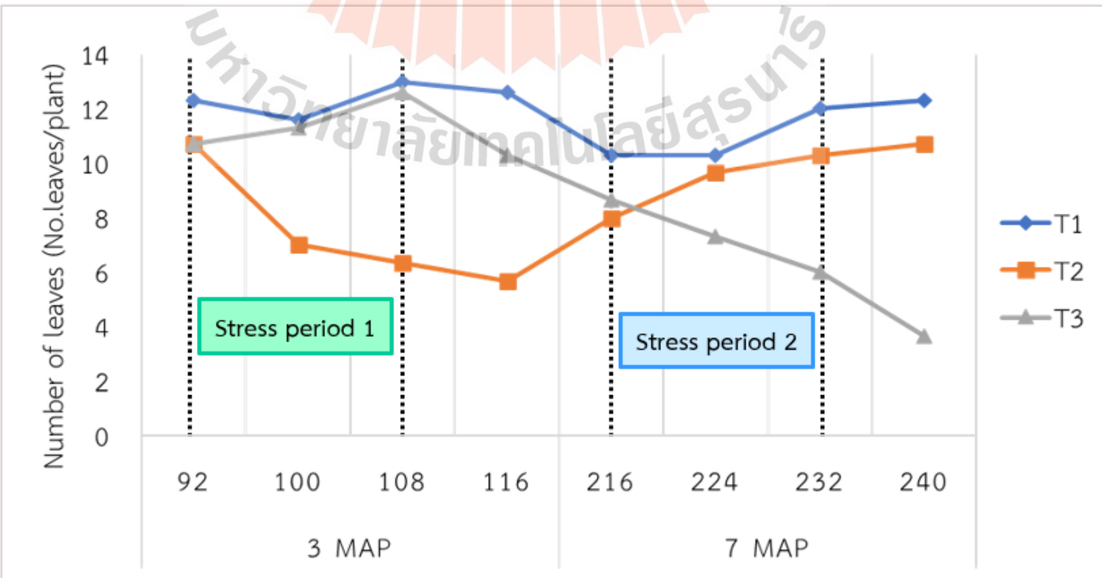

Figure 4.3 Effects of irrigation methods on the number of leaves.

4.2.2 Physiological process

4.2.2.1 SCMR

The SCMR result is shown in Figure 4. During stress period 1, irrigation treatment (T1) tended to have the highest SCMR values, while T2 had the lowest values. During stress period 2, the water deficit at 7 MAP (T3) produced the lowest SCMR, while the water deficit at 3 MAP (T2) had similar SCMR values to irrigation treatments (T1) (Figure 4.4).

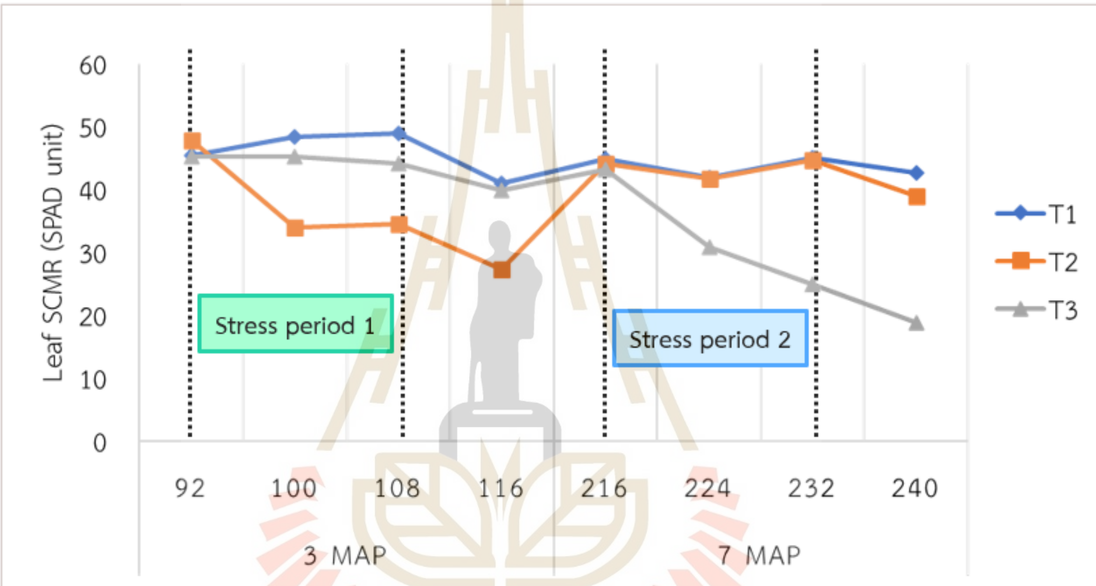

Figure 4.4 Effects of irrigation methods on SCMR.

4.2.2.2 Leaf water potential (LWP)

T2 had lower LWP than T1 and T3 at stress period 1. During stress period 2, water deficit at 7 MAP (T3) had the lowest LWP, while the water deficit at 3 MAP (T2) and irrigation treatments (T1) had similar higher LWP (Figure 4.5).

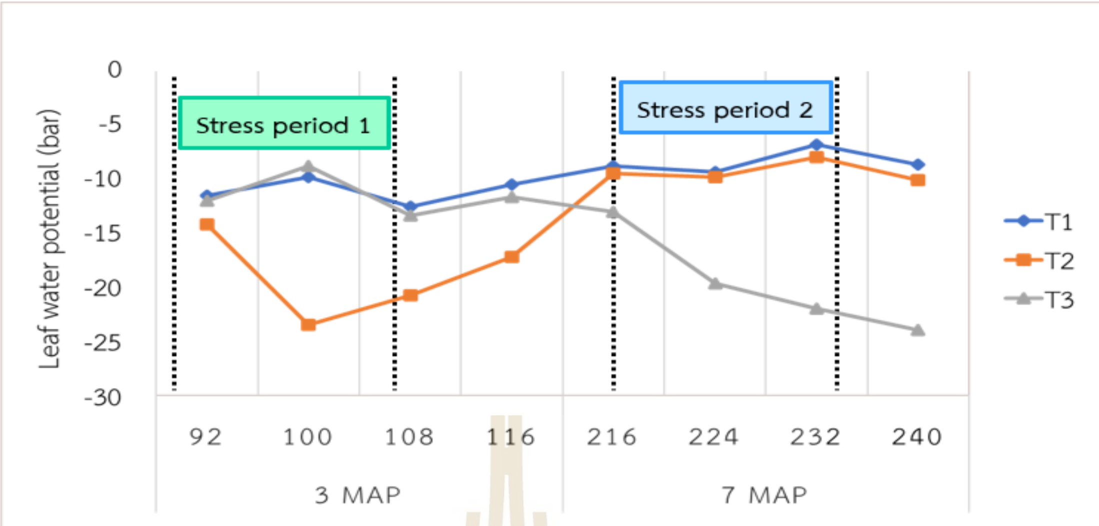

Figure 4.5 Effects of irrigation methods on leaf water potential.

4.2.2.3 Photosynthetic rate

The measurement of leaf photosynthetic rate of sugarcane found that T2 tended to produce a lower photosynthetic rate than irrigation treatment (T1), and the water deficit at 7 MAP (T3) during stress period 1. While at stress period 2, irrigation treatment (T1) tended to produce a higher photosynthetic rate than water deficit treatments (T2 and T3) (Figure 4.6).

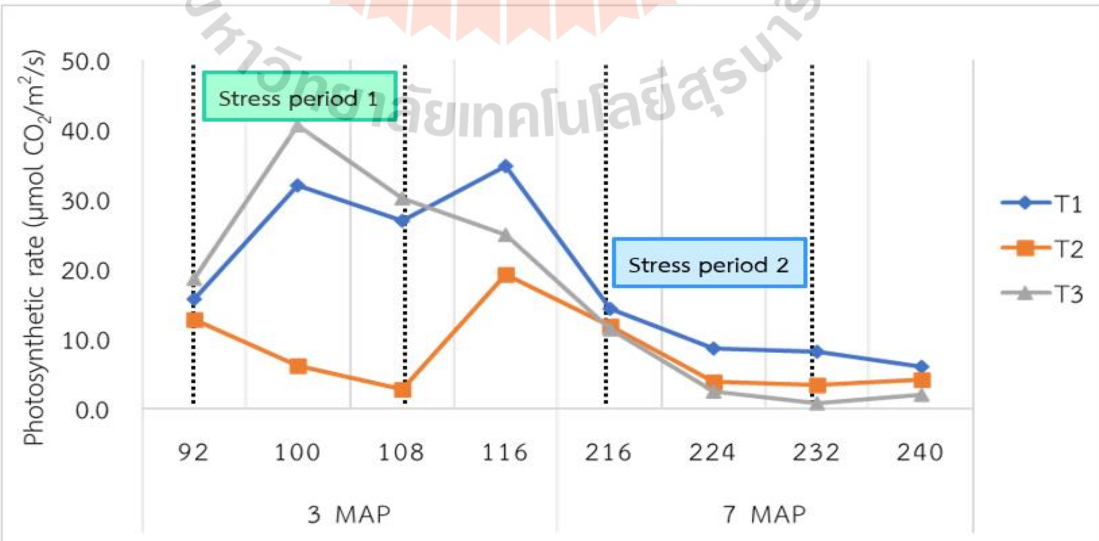

Figure 4.6 Effects of irrigation methods on the photosynthetic rate.

4.2.2.4 Transpiration rate

The result of transpiration rate measurement showed that at stress period 1, T2 produced a lower transpiration rate than irrigation treatment (T1), and the water deficit at 7 MAP (T3). While, at stress period 2, irrigation treatment (T1) tended to produce the highest transpiration rate compared to water deficit treatments (T2 and T3) (Figure 4.7).

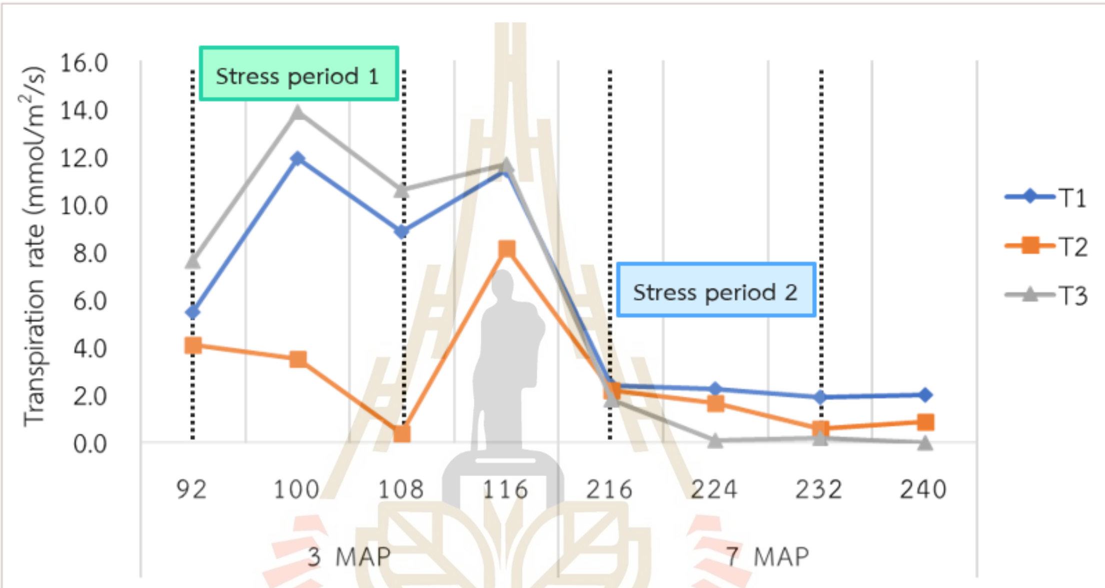

Figure 4.7 Effects of irrigation methods on transpiration rate.

4.2.2.5 Stomatal conductance

The result of leaf stomatal conductance measurement found that, at stress period 1, water deficit at 3 MAP (T2) had lower stomatal conductance than irrigation treatment (T1) and the water deficit at 7 MAP (T3). While during stress period 2, the irrigation treatment (T1) and water deficit at 3 MAP (T2) produced higher stomatal conductance than water deficit treatments (T3) (Figure 4.8).

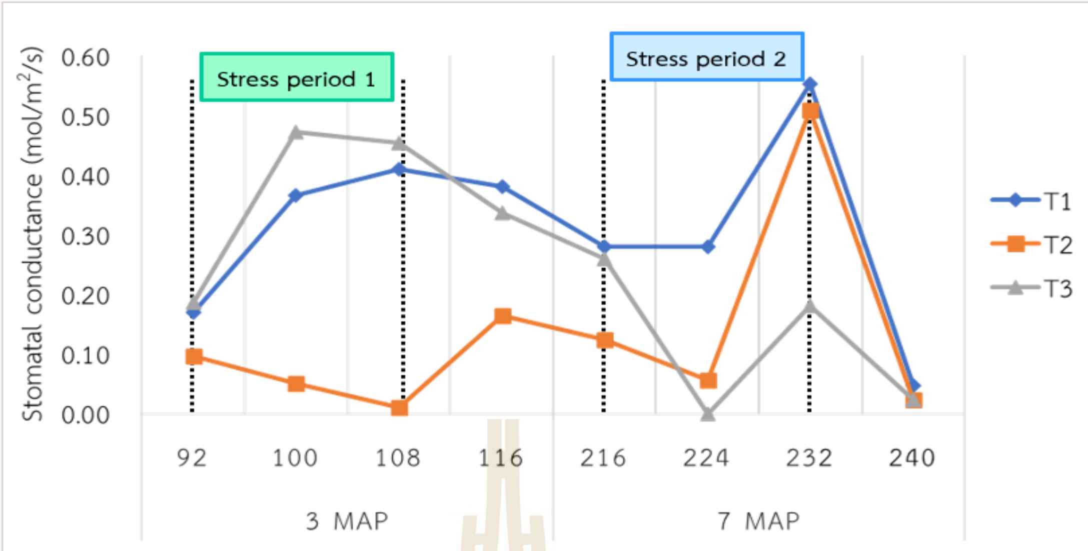

Figure 4.8 Effects of irrigation methods on stomatal conductance.

4.2.3 Yield and Yield components

The yield and yield components analysis is shown in Table 4.6, T1 produced the highest yield (11.8 kg) while T3 produced the lowest yield (7.73 kg). The stalk length, NMC, stalk weight, and total soluble solids (TSS) were not significantly different among treatments, but irrigation treatment (T1) tended to produce higher values than those in water deficit conditions (T2 and T3).

Table 4.6 Effects of irrigation methods on cane yield.

Treatments	Yield (kg)	Stalk length (cm)	Stalk diameter (cm)	NMC (stalk/ pot plant)	Stalk weight (kg/ stalk)	TSS (°Brix)
T1 Irrigation (Control)	11.8^{a}	230	2.75^{ab}	9.00	1.39	21.9
T2 water deficit conditions at 3 MAP	8.17^{ab}	206	2.65^{b}	7.00	1.18	21.6
T3 water deficit conditions at 7 MAP	7.73^{b}	185	3.00^{a}	7.00	1.11	20.1
F-test	*	ns	*	ns	ns	ns
CV (%)	15.6	9.23	3.24	7.53	22.4	10.9

[1] Means in the same columns with different letters are significant differences based on DMRT at P < 0.05.

This experiment was conducted to compare the effects of 2 water deficit methods (water deficit conditions at 3 and 7 months) and full irrigation under greenhouse conditions. Different irrigation methods resulted in growth and yield differences. Plant height tended to be the lowest in water deficit conditions at 3 MAP (T2) while the irrigation (T1) and water deficit conditions at 7 MAP (T3) tended to produced similarly higher plant height at this period. The effects of water deficit in the early growth stage, cause plants to halt their growth in many aspects. According to Khonghintaisong et al. (2017) research, it was found that during the water deficit in the early growth stage (90-135 DAP), KK3 cultivar had a decrease in the rate of daily height increment, especially during 105-120 DAP. Since this experiment was systematic management of the water supply under the greenhouse, the weather conditions didn't affect growth. The KK3 cultivar showed a decreased growth in both plant height and shoot number when faced the water deficit (Khonghintaisong et al., 2017). During stress period 1, especially during the first 3-4 months, as the soil moisture in the pots gradually decreased, competition between the plants cane, affected tillering and leaf production. The plant-maintained balance in the plant by dropping the leaves, causing reduced leaf production. The results were similar to Kapetch et al. (2010) who reported that during the soil receiving insufficient moisture content, the number of shoots per rai of no irrigation treatment was reduced more than in other irrigation methods and the value had relatively stable until harvesting. Ethan et al. (2016) also reported that the deficit irrigation at the mid-season stage had the greatest impact on sugarcane yield as the NMC at harvesting had reduced by 18.6% compared to full irrigation treatment. Endres et al. (2018) reported that the effect of water deficit mostly affected the leaf number of sugarcane during the early growth stage. During stress period 2, water deficit conditions at 7 months (T3) (the elongation stage), the number of shoots had reduced only slightly, but it had the greatest impact on productivity. When returning to the irrigation, the number of shoots increased slightly but it had the greatest impact on the NMC at harvest. The results were similar to Dingre & Gorantiwar (2021) who reported that water deficit in the elongation stage had the greatest impact on yields. Mall et al. (2016) also reported that one of the key growth phases affecting sugarcane yield was the elongation stage. Hsiao (1973) reported that water deficit primarily affected leaf formation and stem elongation.

The SCMR is the tool that indirectly detect the chlorophyll content and leaf nitrogen status. Jangpromma et al. (2010) found that the SCMR was a rapid tool for chlorophyll detectors. Nageswara Rao et al. (2001) and Richardson et al. (2002) found that leaf chlorophyll positively related to leaf nitrogen. In this study, the result showed that drought stress conditions at an initial stage (T2) and elongation stage (T3) had lower leaf SCMR than under the water-sufficient conditions (T1). A similar result of Arunyanark et al. (2009) found that drought stress influenced SCMR and Jangpromma et al. (2012) also found that the drought condition was an impact factor to reduce the chlorophyll content.

For physiological traits analysis (photosynthesis, transpiration, and stomatal conductance) and leaf water potential, the result showed that the lowest physiological traits, and LWP were found in drought stress at an early stage (T2) and elongation stage (T3). However, under rewatering conditions, sugarcane could recover by increasing the physiological traits and LWP more than under drought stress conditions but still did not recover up to the level of water-sufficient conditions. The result was similar to De Almeida Silva et al. (2011) and Dos Santos et al. (2014) who found that the water deficit condition was negatively related to photosynthesis, stomatal conductance, water transpiration, and leaf water potential. Chen et al. (2012) and Jongdee et al. (2002) also found that the water stress conditions which limited the available water in the soil had an effect of reducing sugarcane LWP.

The sugarcane yield and yield components of the water deficit and full irrigation methods were different. Full irrigation treatment (T1) produced the highest stalk length, stalk weight, NMC, TSS, and yield while water deficit treatment produced the lowest of all parameters. Similar result was reported by Ethan et al. (2016) who showed that the highest stalk height of 207.4 cm was found in full irrigation while the lowest stalk height of 189.4 cm was found under drought stress in the mid-season stage and sugarcane yield of 11.9 tons/rai was found under water deficit during the mid-season stage and yield of 15.7 tons/rai was found under fully irrigation treatments.

Soil moisture during 1-2 MAP was sufficient in all treatments as the same amount of water calculated at FC value was given to the sugarcane at the beginning in all treatments. However, after applying the water deficit conditions at 3 month (tillering stage) and 7 months (stalk elongation stage) resulted to the reduction of sugarcane growth in that period due to stress conditions but when returning to the irrigation, sugarcane could recover in both stress phases but was still not equivalent to the full irrigation treatment causing the reduction of final cane yield in both stress treatment comparing to full irrigation treatment. The results were similar to other studies by Doorenbos et al. (1980) who reported that water stress during the germination stage, tillering stage, and elongation stage were most sensitive to yield, and the maturation phase was least sensitive to water stress. Rossler et al. (2013) reported that water stress during the stalk elongation phase reduced cane yield by 6-11 tons/ha (5-9 %). Puengpa & Boontham (2012) reported the appropriate amount of soil water in each stage of the sugarcane growth period especially at the elongation stage was a positively correlated to sugarcane growth and yield.

4.3 Experiment 3: Controlling drip irrigation for sugarcane by the wireless sensor system.

4.3.1 Water requirement and water supply of sugarcane

4.3.1.1 Monthly water requirement and water supply

The monthly water requirement and water supply for sugarcane production in SCL soil and LS soil are shown in Figures 4.9 and 4.10 respectively. The monthly water requirement increased with the age of sugarcane and reached the maximum value of 185 mm in June in SCL soil and May in LS soil, after that the water requirement decreased until harvest.

The rainfall pattern was similar in both soils in which the highest rainfall of 195 and 292 mm appeared in September and August in SCL soil and LS soil respectively.

The amount of water supply was calculated according to the water requirement of sugarcane and the effective rainfall which was estimated by the Daily

Soil Moisture Balance Method (FAO, 1998). Normally sugarcane requires the water supply for ten months throughout the year. The highest water supply given to the SCL soil was 145 mm in April, but to the LS soil was 158 mm in June. There were relationships between rain, water requirement, and water supply. When the total water requirement of sugarcane was explicit, the more rainfall, the less water supply. Therefore, the water supply is dependent on the weather conditions in the growing season of each area.

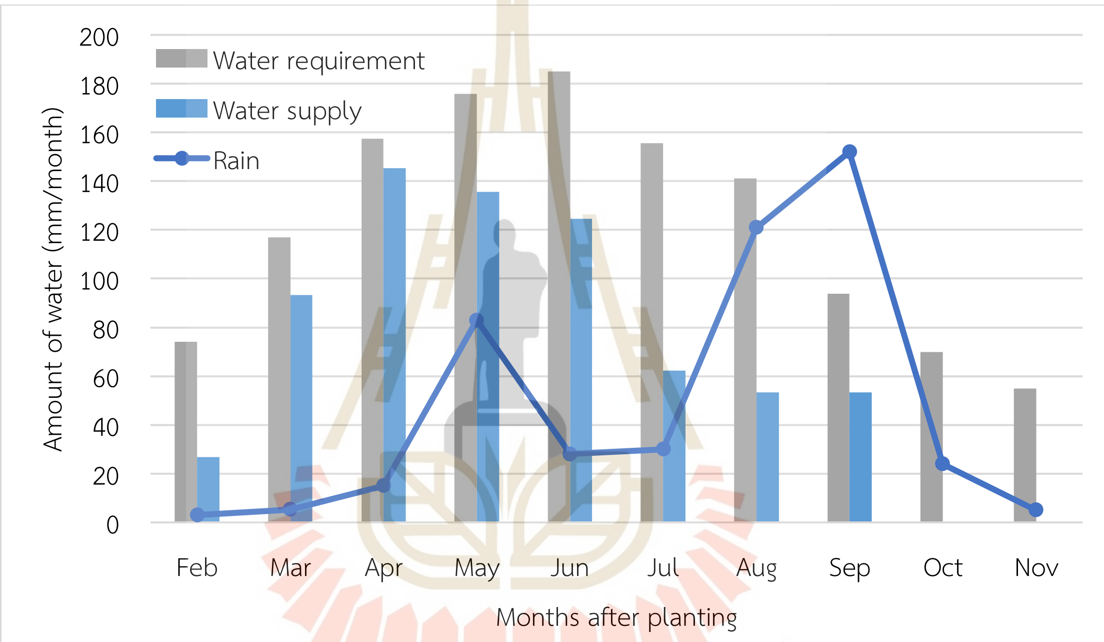

Figure 4.9 Water requirement and water supply of sugarcane in SCL soil during the planting season 2019/20.

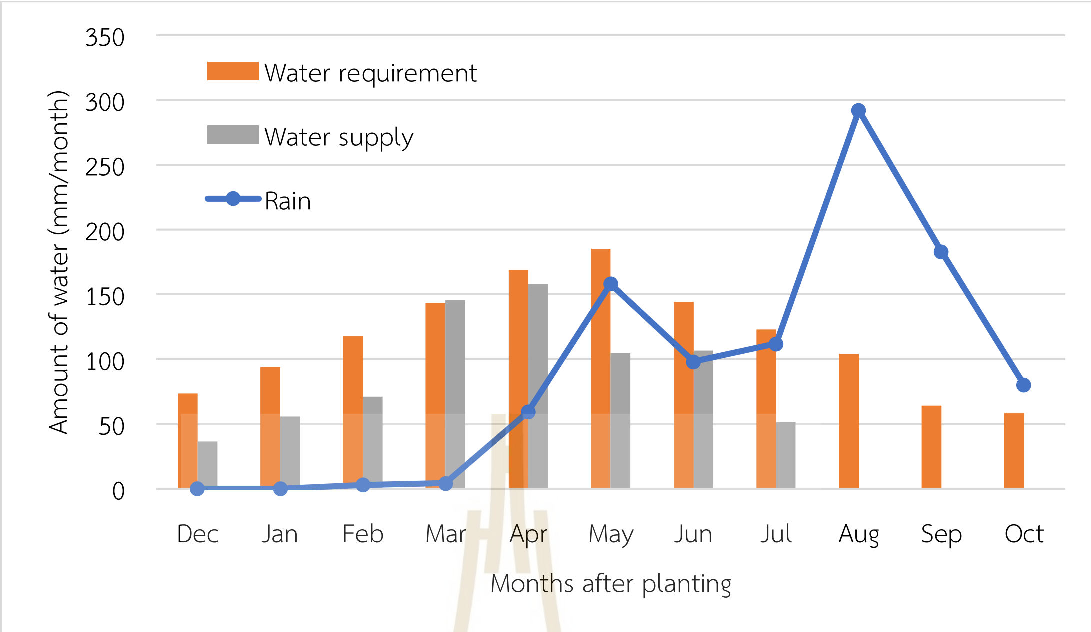

Figure 4.10 Water requirement and water supply of sugarcane in LS soil during the planting season 2018/19.

4.3.1.2 Total water requirement and water supply

The total water requirement and water supply are shown in Table 4.7 for SCL soil and Table 29 for LS soil. In SCL soil, sugarcane had a water requirement of 1,224 mm, but during the growing period, the average rainfall was only 253 mm, which was insufficient for the requirement of sugarcane. Therefore, the drip irrigation system irrigated the sugarcane to receive sufficient water to meet the requirements. The drip irrigation controlled by the water balance model (T2-T3) was irrigated 19 times with total irrigation water of 694 mm and the drip irrigation system controlled by the sensor (T4) was irrigated 14 times with total irrigation water of 548 mm. The result demonstrated that T4 used less irrigation water than T2 and T3. In contrast, T4 was the higher yield and yield component in this soil.

Table 4.7 Effects of irrigation methods on water total water requirement and water supply in SCL soil.

Treatment	Rainfall (mm)	Effective rainfall* (mm)	Irrigation water (mm)	Water requirement (mm)	Amount of water received ** (mm)	Number of irrigation supply
T1	466	253	-	1,224	253	-
T2	466	253	694	1,224	947	19
T3	466	253	694	1,224	947	19
T4	466	253	548	1,224	801	14

T1 = Control, T2 = Drip irrigation + water balance model + Soil fertilizer, T3 = Drip irrigation + water balance model + Fertigation, T4 = Drip irrigation + sensor + Fertigation

* Effective rainfall estimated by Daily Soil Moisture Balance Method

** Amount of water received = Effective rainfall + Irrigation water

In LS soil, sugarcane had a water requirement of 1,276 mm, but the average rainfall was 530 mm., which was also insufficient. The drip irrigation controlled by the water balance model (T2-T3) was irrigated 22 times with total irrigation water of 729 mm, while the drip irrigation controlled by the sensor (T4) was irrigated 17 times with total irrigation water of 640 mm. Similar to SCL soil, in this soil T4 also used less irrigation water (Table 4.8) and the yield was also higher than T2 and T3.

Table 4.8 Effects of irrigation methods on water total water requirement and water supply in LS soil.

Treatment	Rainfall (mm)	Effective rainfall* (mm)	Irrigation water (mm)	Water requirement (mm)	Amount of water received ** (mm)	Number of irrigation supply
T1	990	530	-	1,276	530	-
T2	990	530	729	1,276	1,259	22
T3	990	530	729	1,276	1,259	22
T4	990	530	640	1,276	1,170	17

T1 = Control, T2 = Drip irrigation + water balance model + Soil fertilizer, T3 = Drip irrigation + water balance model + Fertigation, T4 = Drip irrigation + sensor + Fertigation

* Effective rainfall estimated by Daily Soil Moisture Balance Method

** Amount of water received = Effective rainfall + Irrigation water

4.3.2 Soil water potential during the growing season of sugarcane

4.3.2.1 Soil moisture content of all treatments

The average soil water potentials at the depth of 20 - 40 cm from April to July in SCL soil and from March to June in LS soil are shown in Figures 4.11 and 4.12 respectively.

In SCL, the irrigation treatments (T2-T4) had the level of soil water potential mostly between the field capacity (FC) and critical point of the soils (-30 to-90 centibar). In contrast, T1 had lower soil water potential than the critical point (-90 centibar) except after rainfall events (Figure 4.11). Similarly, in LS soil, the soil water potential (T2-T4) was mostly in the available water holding capacity range and T1 had the lowest soil water potential (-196 centibar), which was below the critical point (-90 centibar) (Figure 4.12).

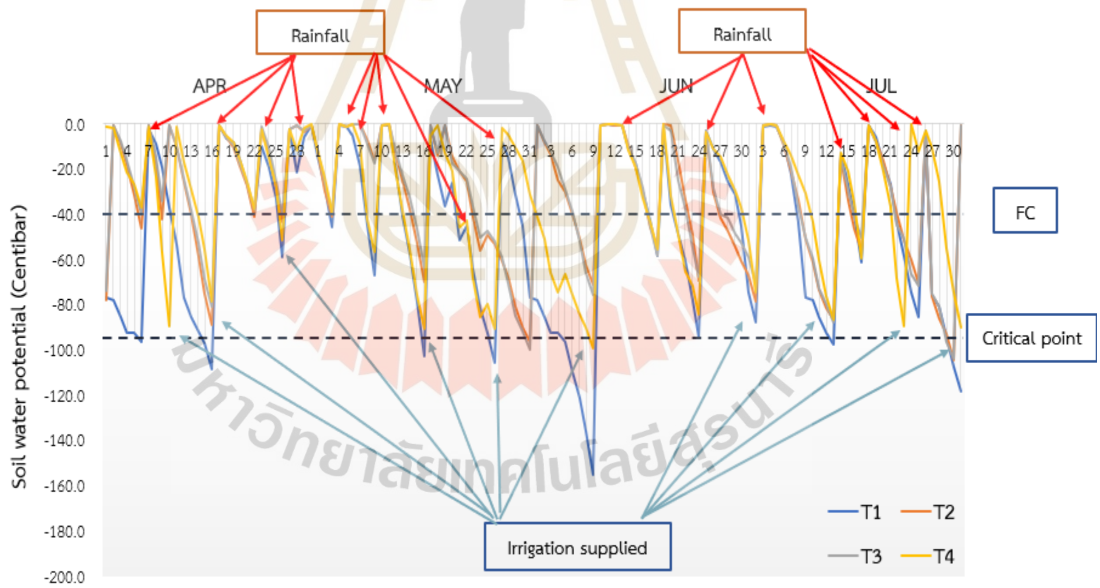

Figure 4.11 Effect of irrigation method on the humidity in SCL soil.

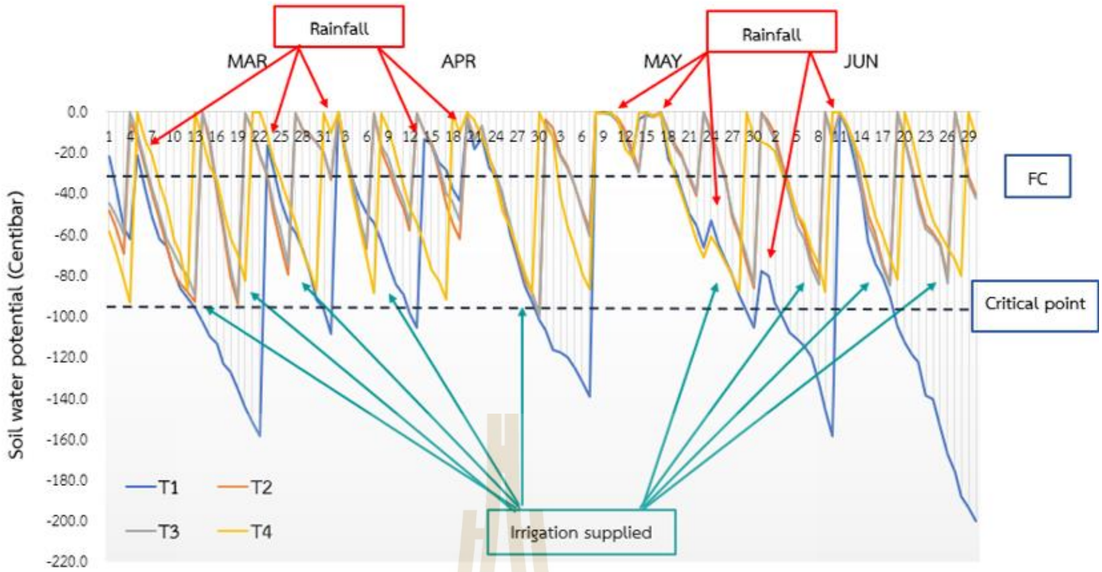

Figure 4.12 Effect of irrigation method on the humidity in LS soil.

4.3.2.2 Comparison of soil water potential between irrigation controlled by the water balance model and by a wireless sensor

Figures 4.13 and 4.14 show the comparison of soil water potential between T3 and T4 in SCL and LS soil. The irrigation treatment (T3-T4) had soil water potential mostly in the range between FC and critical point. However, they had different patterns of soil moisture during the monitoring period leading to different water supply patterns and amounts. T4 had less irrigation water supply than T3. In T4, the water application was based on the direct measurement of soil moisture using a watermark sensor which should be more accurate. While in the irrigation controlled by the water balance model (T3), the water application was based on indirect estimated soil water content. In this method, the soil moisture was estimated from water application, rainfall, and crop evapotranspiration (ETc) which was calculated from the historic weather conditions and crop coefficient (Kc). Therefore, the estimated soil water content might not be as accurate as the direct measurement in T4.

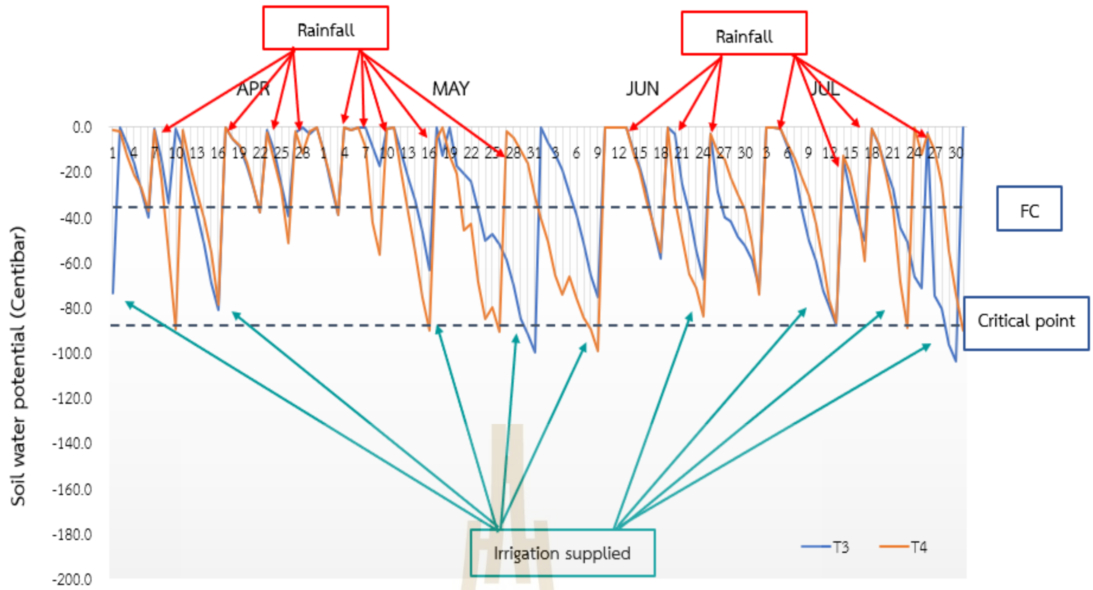

Figure 4.13 Comparison of soil water potential between irrigation controlled by water balance model and by a wireless sensor in SCL soil.

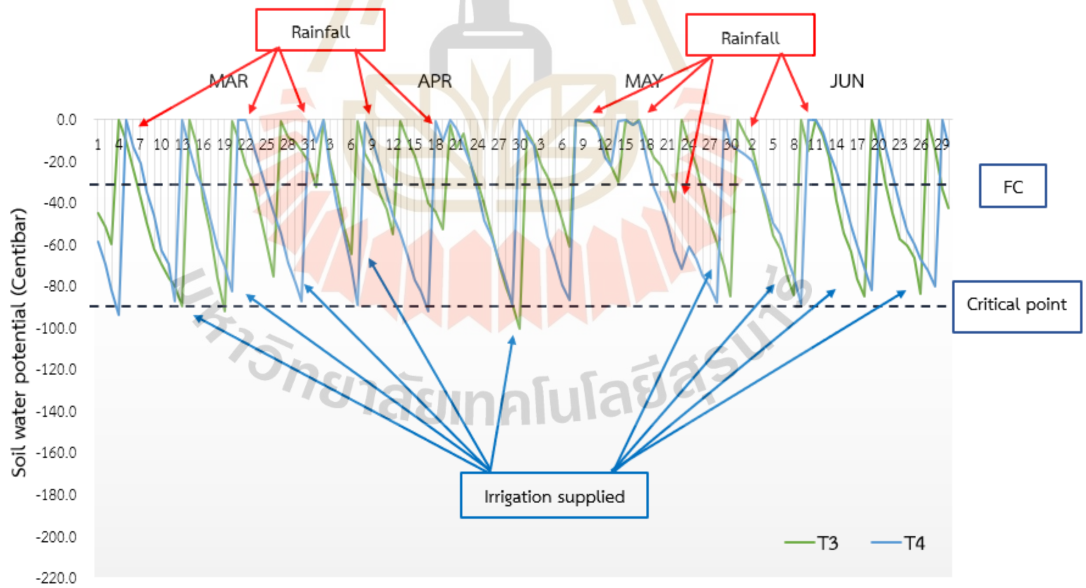

Figure 4.14 Comparison of soil water potential between irrigation controlled by water balance model and by a wireless sensor in LS soil.

4.3.3 Sugarcane growth

4.3.3.1 Plant height

In SCL soil, it was found that plant height in irrigation treatments (T2-T4) was significantly greater than those in no irrigation treatment (T1) at all MAP. Among irrigation treatments, plant height was statistically different. T4 was the highest plant height at all MAP (Table 4.9).

Table 4.9 Effects of irrigation methods on plant height in SCL soil.

Treatment	Plant height (cm)		
	2 MAP	4 MAP	6 MAP
T1: Control	23.7^{c}	77.9^{b}	116^{b}
T2: Drip irrigation + WB model + Soil fertilizer	28.7^{b}	110^{a}	158^{a}
T3: Drip irrigation + WB model + Fertigation	31.1^{ab}	109^{a}	161^{a}
T4: Drip irrigation + sensor + Fertigation	33.0^{a}	113^{a}	165^{a}
F-test	**	**	**
CV (%)	5.79	6.98	7.53

[1] Means in the same columns with different letters are significant differences based on DMRT at P < 0.05.

In LS soil, it was found that plant height in irrigation treatments (T2-T4) was also significantly greater than those in no irrigation treatment (T1) at all MAP. Among irrigation treatments, plant height was significantly different only at 2 and 4 MAP. T2 produced the highest plant height at 2 and 4 MAP, while at 6 MAP, plant height was not significantly different among irrigation treatments (Table 4.10).

Table 4.10 Effects of irrigation methods on plant height in LS soil.

Treatment	Plant height (cm)		
	2 MAP	4 MAP	6 MAP
T1: Control	9.5^{c}	23.8^{c}	147^{b}
T2: Drip irrigation + WB model + Soil fertilizer	18.6^{a}	48.8^{a}	192^{a}
T3: Drip irrigation + WB model + Fertigation	13.2^{bc}	37.7^{b}	171^{a}
T4: Drip irrigation + sensor + Fertigation	14.3^{b}	36.4^{b}	194^{a}
F-test	**	**	*
CV (%)	17.0	17.3	8.08

[1] Means in the same columns with different letters are significant differences based on DMRT at P < 0.05.

4.3.3.2 Shoot number

In SCL soil, the shoot number in drip irrigation treatments (T2-T4) was significantly higher than those in control (T1) at 2 MAP. Among irrigation treatments, shoot number was statistically different in which T4 produced the highest shoot number at 4 and 6 MAP (Table 4.11).

Table 4.11 Effects of irrigation methods on shoot number in SCL soil.

Treatment	Shoot number (No./rai)		
	2 MAP	4 MAP	6 MAP
T1: Control	20,913[c]	17,951	12,494
T2: Drip irrigation + WB model + Soil fertilizer	24,198[ab]	20,395	13,704
T3: Drip irrigation + WB model + Fertigation	22,197[bc]	21,161	15,309
T4: Drip irrigation + sensor + Fertigation	26,050[a]	21,531	15,654
F-test	*	ns	ns
CV (%)	5.67	8.85	8.26

[1] Means in the same columns with different letters are significant differences based on DMRT at $P < 0.05$.

In LS soil, the shoot number in drip irrigation treatments (T2-T4) was also significantly higher than those in control (T1) at 2 and 4 MAP. Among irrigation treatments, T2 produce the highest shoot number at 4 MAP while T4 tended to produce the highest shoot number at 6 MAP (Table 4.12).

Table 4.12 Effects of irrigation methods on shoot number in LS soil.

Treatment	Shoot number (No./rai)		
	2 MAP	4 MAP	6 MAP
T1: Control	12,426[c]	18,941[c]	12,103
T2: Drip irrigation + WB model + Soil fertilizer	24,897[a]	25,824[a]	12,956
T3: Drip irrigation + WB model + Fertigation	19,529[ab]	24,647[b]	12,603
T4: Drip irrigation + sensor + Fertigation	18,985[b]	24,235[b]	13,103
F-test	**	**	ns
CV (%)	18.2	3.95	7.09

[1] Means in the same columns with different letters are significant differences based on DMRT at $P < 0.05$.

4.3.4. SCMR

In SCL soil, it was found that the SCMR in all treatments was not significantly different at 4 MAP. T4 tended to produce the highest SCMR (44.7) at 4 MAP. While at 6 MAP, the highest SCMR was obtained from T4 (40.3) compared to T2 (39.8), T3 (39.5), and T1 (32.3) (Table 4.13).

Table 4.13 Effects of irrigation methods on SCMR in SCL soil.

Treatment	SCMR (SPAD unit)	
	4 MAP	6 MAP
T1: Control	40.7	32.3[b]
T2: Drip irrigation + WB model + Soil fertilizer	40.9	39.8[a]
T3: Drip irrigation + WB model + Fertigation	42.4	39.5[a]
T4: Drip irrigation + sensor + Fertigation	44.7	40.3[a]
F-test	ns	**
CV (%)	3.96	2.00

[1] Means in the same columns with different letters are significant differences based on DMRT at P < 0.05.

In LS soil, it was found that the SCMR of all treatments was not significantly different at all MAP. However, T4 tended to produce the highest SCMR at 4 MAP (41.9) while T2 tended to produce the highest SCMR at 6 MAP (Table 4.14).

Table 4.14 Effects of irrigation methods on SCMR in LS soil.

Treatment	SCMR (SPAD unit)	
	4 MAP	6 MAP
T1: Control	40.1	39.6
T2: Drip irrigation + WB model + Soil fertilizer	41.4	41.9
T3: Drip irrigation + WB model + Fertigation	41.4	39.9
T4: Drip irrigation + sensor + Fertigation	41.9	40.4
F-test	ns	ns
CV (%)	5.03	4.75

[1] Means in the same columns with different letters are significant differences based on DMRT at P < 0.05.

4.3.5 Plant nutrients of the leaf

The leaf nutrient analysis showed that leaf N, P, K, Ca, and Mg were not significantly different between treatments. However, irrigation treatments (T2-T4) tended to have higher leaf nutrients than those in the rainfed treatment (T1).

The comparison of the leaf analysis to the standard nutrient content found that N and P in all treatments were lower than the standard nutrient content, K content was comparable to the standard value and Mg content was higher compared to the standard value. For Ca content, T4 was comparable but T1-T3 was lower than the standard value in SCL soil (Table 4.15).

Table 4.15 Effects of irrigation methods on plant nutrients of leaf in SCL soil at 4 MAP.

Treatment	Plant nutrient of leaf				
	N (%)	P (%)	K (%)	Ca (%)	Mg (%)
T1: Control	1.04	0.16	1.24	0.19	0.48
T2: Drip irrigation + WB model + Soil fertilizer	1.14	0.17	1.31	0.20	0.52
T3: Drip irrigation + WB model + Fertigation	1.09	0.17	1.26	0.21	0.51
T4: Drip irrigation + sensor + Fertigation	1.20	0.18	1.41	0.27	0.53
F-test	ns	ns	ns	ns	ns
CV (%)	9.85	21.0	13.2	13.2	11.1
Suitable nutrient content in sugarcane leaves	2.00-2.60	0.22-0.30	1.00-1.60	0.22-0.45	0.15-0.32

[1] Means in the same columns with different letters are significant differences based on DMRT at P < 0.05.

In LS soil, the leaf calcium was significantly different, but N, P, K, and Mg were not significantly different between treatments. The irrigation treatments (T2-T4) had higher Ca (1.16, 1.10, and 1.10%, respectively) than the rainfed treatment (T1). N, P, and K content in irrigation treatments (T2-T4) tended to be higher than in the rainfed treatment.

In the comparison of the leaf analysis and the standard nutrient content, it was found that N and P in all treatments were lower than the standard nutrient content and K content was comparable to the standard value. Ca and Mg content was higher compared to the standard value (Table 4.16).

Table 4.16 Effects of irrigation methods on plant nutrients of leaf in LS soil at 4 MAP.

Treatment	Plant nutrient of leaf				
	N (%)	P (%)	K (%)	Ca (%)	Mg (%)
T1: Control	1.33	0.14	1.14	0.75^{b}	0.29
T2: Drip irrigation + WB model + Soil fertilizer	1.41	0.15	1.28	1.16^{a}	0.28
T3: Drip irrigation + WB model + Fertigation	1.40	0.17	1.48	1.10^{a}	0.35
T4: Drip irrigation + sensor + Fertigation	1.41	0.18	1.46	1.10^{a}	0.36
F-test	ns	ns	ns	*	ns
CV (%)	5.52	13.4	11.3	10.1	21.9
Suitable nutrient content in sugarcane leaves	2.00-2.60	0.22-0.30	1.00-1.60	0.22-0.45	0.15-0.32

[1] Means in the same columns with different letters are significant differences based on DMRT at P < 0.05.

4.3.6 Yield and yield components

In SCL soil, the treatments significantly affected cane yield, stalk length, NMC and TSS. T4 produced the highest cane yield (19.0 tons/rai), stalk length (262 cm), NMC (14,889 stalks/rai), and TSS (24.6 °Brix), while the lowest cane yield (12.2 tons/rai), stalk length (192 cm), NMC (11,432 stalks/rai), and TSS (23.5 °Brix) were recorded in T1. The stalk diameter and stalk weight were not significantly different among treatments, but drip irrigation treatments (T2-T4) tended to produce higher than those in rainfed treatment (T1) (Table 4.17).

Table 4.17 Effects of irrigation on cane yield in SCL soil.

Treatment	Cane yield (tons/rai)	Stalk length (cm)	Stalk diameter (cm)	Stalk weight (kg/stalk)	NMC (stalk/rai)	TSS (°Brix)
T1	12.2^{c}	192^{b}	2.93	1.06	$11,432^{c}$	23.5^{b}
T2	16.3^{b}	240^{a}	3.00	1.30	$12,914^{bc}$	24.0^{ab}
T3	17.6^{ab}	245^{a}	2.96	1.27	$13,827^{ab}$	24.6^{a}
T4	19.0^{a}	262^{a}	2.96	1.28	$14,889^{a}$	24.1^{ab}
F-test	**	**	ns	ns	**	*
CV (%)	5.61	4.58	6.03	11.8	6.09	1.35

T1 = Control, T2 = Drip irrigation + water balance model + Soil fertilizer, T3 = Drip irrigation + water balance model + Fertigation, T4 = Drip irrigation + sensor + Fertigation

[1] Means in the same columns with different letters are significant differences based on DMRT at P < 0.05.

In LS soil, T4 produced the highest cane yield (21.3 ton/rai), stalk length (323 cm), NMC (12,792 stalks/rai), and TSS (21.8 ^{o}Brix), while T1 had the lowest all of those yield and yield components. The stalk diameter and stalk weight were not significantly different among treatments, but drip irrigation treatments (T2-T4) tended to produce higher than those in rainfed treatment (T1) (Table 4.18).

Table 4.18 Effects of irrigation on cane yield in LS soil.

Treatment	Cane yield (tons/rai)	Stalk length (cm)	Stalk diameter (cm)	Stalk weight (kg/stalk)	NMC (stalk /rai)	TSS (^{o}Brix)
T1	16.9^{b}	272^{b}	2.72	1.51	$11,719^{b}$	19.8^{b}
T2	20.8^{ab}	314^{a}	2.76	1.69	$12,644^{ab}$	20.8^{ab}
T3	20.6^{ab}	284^{ab}	2.92	1.70	$12,656^{ab}$	21.4^{ab}
T4	21.3^{a}	323^{a}	2.84	1.70	$12,792^{a}$	21.8^{a}
F-test	*	*	ns	ns	*	*
CV (%)	10.1	6.00	4.72	9.96	4.73	3.72

T1 = Control, T2 = Drip irrigation + water balance model + Soil fertilizer, T3 = Drip irrigation + water balance model + Fertigation, T4 = Drip irrigation + sensor + Fertigation

[1] Means in the same columns with different letters are significant differences based on DMRT at P < 0.05.

4.3.7 Irrigation water and fertilizer use efficiency

In SCL soil, it was found that all irrigation treatments had significantly different irrigation water use efficiency (IWUE). T4 had the highest (23.7 kg/mm/rai) and was different from other irrigation treatments (T2 and T3). For fertilizer use efficiency (FUE) analysis, it was found that all irrigation treatments (T2-T4) had significantly higher N, P, and K FUE than T1. T4 produced the higher FUE of N (0.91 tons/kg), P (1.19 tons/kg), and K content (1.27 tons/kg) than T1 N (0.58 tons/kg), P (0.76 tons/kg), and K content (0.81 tons/kg) (Table 4.19).

Table 4.19 Effects of irrigation methods on irrigation water and fertilizer use efficiency in SCL soil.

Treatment	IWUE (kg/mm/rai)	FUE (tons/kg)		
		N	P_2O_5	K_2O
T1: Control	-	0.58^{b}	0.76^{b}	0.81^{b}
T2: Drip irrigation + WB model + Soil fertilizer	17.2^{b}	0.89^{a}	1.17^{a}	1.25^{a}
T3: Drip irrigation + WB model + Fertigation	18.6^{b}	0.84^{ab}	1.10^{ab}	1.17^{ab}
T4: Drip irrigation + sensor + Fertigation	23.7^{a}	0.91^{a}	1.19^{a}	1.27^{a}
F-test	*	*	*	*
CV (%)	14.0	17.6	17.7	17.8

IWUE=Irrigation water use efficiency, FUE=Fertilizer use efficiency

[1] Means in the same columns with different letters are significant differences based on DMRT at $P < 0.05$.

In LS soil (Table 4.20), it was found IWUE was not significantly different among irrigation treatments. However, T4 tended to produce the highest IWUE (18.2 kg/mm/rai) compared to T3 and T2. For FUE, it was found that all treatments had significantly different N and P FUE. T4 produced the higher N FUE (1.04 tons/kg) and P FUE (1.43 tons/kg) than T1 N FUE (0.81 tons/kg) and P FUE (1.11 tons/kg). K FUE in all treatments was not significantly different but T4 tended to produce the highest K FUE (0.65 tons/kg) in this soil.

Table 4.20 Effects of irrigation methods on irrigation water and fertilizer use efficiency in LS soil.

Treatment	IWUE (kg/mm/rai)	FUE (tons/kg)		
		N	P_2O_5	K_2O
T1: Control	-	0.81^{b}	1.11^{b}	0.51
T2: Drip irrigation + WB model + Soil fertilizer	16.5	0.97^{ab}	1.33^{ab}	0.61
T3: Drip irrigation + WB model + Fertigation	16.4	0.93^{ab}	1.28^{ab}	0.58
T4: Drip irrigation + sensor + Fertigation	18.2	1.04^{a}	1.43^{a}	0.65
F-test	ns	*	*	ns
CV (%)	14.2	14.7	14.8	15.2

[1] Means in the same columns with different letters are significant differences based on DMRT at $P < 0.05$.

The water requirement of sugarcane was in the range of 1,100–2,500 mm/season (Carr & Knox, 2011; FAO, 2011), and the highest daily ETc rates of 6.07 mm d−1 calculated based on the Penman-Monteith equation (Wonprasaid et al. 2021). The study of Paisancharoen et al. (2012) found that in each year the weather conditions were different. Therefore, sugarcane had different water requirements i.e. sugarcane had a water requirement of 1,591-1,620 mm in 2009/10 and 1,566-1,654 mm in 2010/11. In the irrigation controlled by water balance, the total water requirement of 1,224 and 1,276 mm from planting to harvesting in SCL soil and LS soil was calculated from crop evapotranspiration (ETc). The drip irrigation system controlled by the sensor (T4) provided 548 and 640 mm of irrigation water in SCL and LS soils, respectively, less than the drip irrigation controlled by the water balance model (T2-T3) which provided 694 and 729 mm of irrigation water in SCL and LS soils. Irrigation controlled by sensor (T4), although less irrigation water was applied, sugarcane still had sufficient water to maintain high growth and yield, thus resulted to more water saving than other irrigation methods.

The irrigating patterns, the number of irrigation supplies, and amount of irrigation water were different among treatments. The irrigation treatments (T2-T4) had more water supply than no irrigation treatment (T1). Between the irrigation treatments, the drip irrigation controlled by the water balance model (T3) which was a calculation based on historic weather conditions resulted to more water supply than the drip irrigation system controlled by the sensor (T4) ie. a real-time moisture measurement from the watermark sensor. Theoretically, irrigation based on the current soil moisture monitored by sensor should be more accurate than irrigation controlled by the water balance model as a result of non-uniformity of weather conditions. Currently, various types of humidity sensors were used and has been applied to control watering in various plants such as sugarcane (Wonprasaid et al. 2021) ; (Alamilla et al. 2016), cassava (Xie et al. 2020), barley (Jabro et al. 2020), and tomato (De Oliveira et al. 2021).

For the yield and yield component production, the drip irrigation treatments (T2-T4) which had high growth in the early growth stage (2, 4, and 6 MAP) influenced to higher yield production than the rainfed treatment which had lower growth. The rainfed condition had a high risk of water stress resulting in lower growth and productivity than the drip irrigation treatments. The drip irrigation system controlled by the sensor (T4) had a little higher growth and yield than the drip irrigation controlled by the water balance model (T2-T3) probably due to the more accuracy in water application. The drip irrigation system controlled by the sensor (T4) produced the highest yield of 19.0 and 21.3 tons/rai in SCL and LS soils, respectively. While the drip irrigation controlled by the water balance model (T2-T3) produced 16.3-17.6 and 20.6-20.8 tons/rai of sugarcane yield in SCL and LS soils, respectively, and the rainfed treatment had the lowest yields of 12.2 and 16.9 tons/rai in SCL and LS soils, respectively. The results were similar to Zafar et al. (2020) who reported that the sensor-based drip irrigation system (SD) produced higher yield 13.9-30.5 % and could save more water compared to conventional irrigation.

The drip irrigation system controlled by the sensor (T4) had higher IWUE than the drip irrigation controlled by the water balance model (T2-T3). Since T4 was a real-time moisture measurement, it provides accurate amount of water to meet crop water demand and no excess of water resulting in greater irrigation efficiency than irrigation based on calculated from historical weather conditions (T2 and T3). A study by Wonprasaid et al. (2021), who studied the effects of drip irrigation in sugarcane and found that drip irrigation control by sensor increased IWUE higher than traditional irrigation (water balance models), due to it tended to have a higher yield production and saved more water by 6.9%. A study on cassava by Xie et al. (2020) also found similar results that using sensors to control irrigation saved water by 10-80% compared to irrigation based on the water balance model.

In the comparison of FUE, the result showed that the fertigation had higher FUE than soil fertilizer application due to the fact that the fertilizer in the soluble form of fertilizer in fertigation was readily available and immediately absorbed by plant roots. On the other hand, the granule (solid) fertilizer which was applied in the soil application treatment was not readily available to plant and some fertilizer could be easily loss from the unsuitable conditions. The study by Pawar et al. (2013) who compared the effects of 2 fertilizer applications (soil fertilizer and fertigation), found that 100% drip fertigation had maximum yield and increased FUE by more than 40 % compared with soil fertilizer application. Moreover, it was found that soluble fertilizer in fertigation enhanced FUE by reducing the risk of water and fertilizer loss by 25–30% (Raina et al., 2011).

CHAPTER V
CONCLUSION

5.1 General conclusion

A series of 3 experiments were conducted during 2018 – 2020. The 1st experiment studied the effects of 3 irrigation practices (rain-fed conditions, half water supply, and full water supply) on growth, yield, and yield components of sugarcane. The results found that drip irrigation with a full water supply irrigated water to crop 1,121 mm (close to water requirement) and had the highest average yield of 19.7 ton/rai, which was 19.4% and 31.1% more than drip irrigation with a half water supply and rainfed conditions, respectively. Therefore, this study found that irrigation was essential for sugarcane production in Northeast conditions since it increased yield and yield components. The maximum yield increment derived from the irrigation with water supply at crop water requirement.

The 2nd experiment studied the response of the physiological processes to well-irrigated conditions, water deficit conditions at tillering stage (3 MAP), and water deficit conditions at the stalk elongation stage (7 MAP). It was found that water deficit had influences on the physiological process, growth, and yield of sugarcane. Well-irrigated conditions had the highest photosynthesis rate, transpiration rate, and stomatal conductance and could maintain good water status in the leaf. While water deficit conditions at 3 MAP and 7 MAP had negative effects on all physiological processes. The well-irrigated condition had 44.4% and 52.6% higher cane yield than water deficit conditions at 3 MAP and 7 MAP, respectively. Moreover, it was found that the water deficit in the stalk elongation stage (7 MAP) had a more negative impact on growth and physiological processes and produced a 5.7% lower yield than the water deficit in the tillering stage (3 MAP).

The 3rd experiment compared the effects of drip irrigation controlled by a water balance model and a wireless sensor system on growth, yield, and irrigation water use efficiency (IWUE) of sugarcane. Even though there was no statistically significant difference, the drip irrigation controlled by wireless sensor tended to produce a higher yield than the water balance model. Moreover, in both soil textures, the irrigation controlled by wireless sensor increased IWUE resulting in less irrigation water of 7.1 and 15.5% than irrigation controlled by the water balance model in LS and SCL soil, respectively. The results can be concluded that drip irrigation controlled by a wireless sensor was more accurate compared to the water balance model. Moreover, it was more convenient and easier to be used by farmers compared to the water balance model. However, the cost of wireless sensor was still expensive for small farmers.

5.2 Recommendation

Drip irrigation was essential for sugarcane production in the Northeast conditions but to gain a maximum yield increment, irrigation water supply should be followed a crop water requirement. If there is enough water resource, irrigation should be fully irrigated throughout the growing period. Under water limited resource, half amount of plant water requirement can be applied to maintain reasonable high sugarcane growth and yield. In addition, under water limited resource, the irrigation should be performed to avoid water deficit conditions during critical periods especially at tillering and stalk elongation stage.

Drip irrigation controlled by the wireless sensor had higher precision than the water balance model. However, the cost of the wireless sensor was still expensive for small scale farmers. Therefore, it can be recommended for large scale farmers as the price per unit area will be less expensive.

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APPENDIX

T1: Irrigation (Control)	T2: Water deficit conditions at 3 MAP	T3: Water deficit conditions at 7 MAP

Attached Figure 1 Effects of irrigation (control) and water deficit conditions in pot plant under greenhouse conditions.

Attached Figure 2 Sensor installation.

T1	T2	T3	T4

Attached Figure 3 Effects of irrigation method in sandy clay loam soil (SCL) at 7 month after planting (MAP)

T1	T2	T3	T4

Attached Figure 4 Effects of irrigation method in loamy sand soil (LS) at 7 MAP

BIOGRAPHY

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