1 Growth and Development of Sugarcane (*Saccharum* spp. Hybrid) and Its Relationship with Environmental Factors

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Abstract

The whole duration of sugarcane (*Saccharum* spp. hybrid) production and development are usually divided into four stages such as germination, tillering, elongation, and maturation. Sugarcane growth and development are closely related to environmental factors such as temperature, sunshine, water, air, and nutrients. For commercial sugarcane production, drought, waterlogging, and frost often severely reduced cane yield. Appropriate field management such as fertilization, irrigation, drainage, and weeding at the early growth stage is very important for the yield by ensuring the rational number of plants through good germination and tillering regulation. Water supply, warm weather, and intense sunshine are also important for the elongation stage. During the processing maturation stage, cool and sunny weather with high temperature differences between day and night is beneficial to sugar accumulation in sugarcane.

Keywords

Development · Growth · Environmental factors · Sugarcane · *Saccharum* spp. hybrid

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1.1 Introduction

Sugarcane (*Saccharum* spp. hybrid) is an important member of the grass family Poaceae (Gramineae), subfamily Panicoideae, super tribe Andropogoneae, sub-tribe Saccharinae, and genus *Saccharum* (Watson et al. 1985). Sugarcane planting areas in the world are mainly distributed between the 33rd parallels of north and latitudes but focus between 25th parallels of north and latitude. Based on temperature, the sugarcane planting areas are located in places with an annual mean temperature of 17–18 °C or higher. The altitude of the sugarcane planting area reaches 1500–1600 m in Yunnan Province, China (Li 2010).

Sugarcane is a C_4 ratooning crop and well-cultivated commercially in at least 106 countries of tropical and subtropical areas, which requests hot and humid environments for growth and development (Li 2010; Verma et al. 2021a, b). Sugarcane accumulates high sucrose content in cane (Bonnett and Henry 2011; Cheavegatti-Gianotto et al. 2011). Sugarcane has significant capability for sucrose accumulation in stalks, and sucrose concentration can be as high as 0.7 M in ripen internodes (Moore 1995). Sucrose is synthesized by the carbohydrates from photosynthesis in green leaves of sugarcane plants and then transferred to sink organs, including consuming and storage sinks. In consuming sinks, sucrose is hydrolyzed to produce energy for growing roots, stems, and flowers while translocated to accumulation sink through phloem for storage purposes (Li 2010).

In a sugarcane production cycle, the first planting crop is named as plant crop, and the subsequent crop is called ratoon crop. In plant crop, from planting to harvesting, the growth and development of sugarcane plants include germination stage, seedling stage, tillering stage, grand growth stage, and maturity and ripening stage (Li 2010). Although sugarcane can produce seeds, stalk cuttings or setts are generally used in commercial production. For the breeding purpose, we need to produce sugarcane seeds. As sugarcane seeds are very tiny, whole fuzz is harvested for seed planting (Li 2010).

1.2 Germination Stage

The germination stage is from planting to the accomplishment of germination of buds and root points of seed cane setts. Under the field conditions of commercial production, the time for germination varies greatly from 7 to 110 days, depending on the environmental temperature. In sugarcane, germination implies activation and subsequent sprouting of the vegetative bud and dormant roots on the node. The germination is affected by the external as well as internal factors. The internal factors are bud health and moisture, reducing sugar content, and nutrient status in the sett. The external factors are the soil moisture, soil temperature, and aeration (Gravois et al. 2014; Li 2010; Verma et al. 2020a). During germination, a series of physiological and biochemical changes happen inside seed cane setts. The activities of various enzymes such as invertases, amylases, proteases, and oxidases are increasing, and respiration is rising, which converts the stored nutrients into simple molecules for the growing need of roots, stem, and leaves of the young plants. In general, roots germinate earlier than buds. This stage is crucial to determine the basic plant number, which is the foundation of crop productivity. It is highly important to ensure enough strong plants for achieving high cane yield (Li 2010; Verma et al. 2020b).

1.2.1 Temperature

Temperature affects most sugarcane germination among various environmental factors. The temperatures below 20 °C or above 43.9 °C are not suitable for bud germination. The temperature for initiating bud germination is about 13 °C, good at 25–27 °C, and optimum at 30–32 °C. In a certain range, the germination gets speeding up with the increasing temperature as the enzyme activities and respiration metabolism gets rising. On the contrary, when the temperature decreases, the germination speed slows down. When the soil temperature is above 20 °C, sugarcane germination speeds up, shortens the germination stage, and improves the germination rate. The higher the temperature is, the faster the germination is. However, if the germination speed is too fast, the growth and tillering of the plants are also speeding up, excessive growth may occur, leading to lower tillering rate and weak root development. When the temperature is over 32 °C, the germination is fast, but the seedling quality is low. Over 40 °C, the germination is inhibited. When the temperature is at 13 °C or down, the buds keep dormant. When the temperature is at 0 °C, the germinating buds will be dead; the temperature is at −2 °C, the dormant buds would be destroyed. In some cases, although the temperature is not very low but keeps for long, the young shoots would become very weak and easily suffer from biotic and abiotic stresses, i.e., drought, freezing, diseases, insect pests, flooding, etc. Under a long time of low temperature, all the buds could be dead because of the stress.

The lethal temperature of the top growing point of sugarcane stalk is about −1.5 °C in Southern China, but −2.0 °C to −2.5 °C in Central China. The lateral bud (dormant bud) has stronger chilling resistance than the top growing point, and its lethal temperature is about −3 °C to −5 °C. The germination rate of the chilling injured living buds is decreased dramatically. After frost, the buds kept original healthy color are still normal, those with sugar juice or dark brown color on the surface are dead, and those with light brown color on the surface are chilling injured. The germination test could be used to determine the living state of the buds. Temperature also affects the root germination in seed canes, and the temperature for seed cane root germination is lower than that for bud. In general, the roots start germination at about 10 °C, and the best at 20–30 °C. That is why the roots grow earlier than bud under low-temperature conditions, which is beneficial to resist drought and diseases.

In Southern China, the temperature is high in autumn and spring, planting sugarcane in these seasons germinated fast, and the germination stage is about 15–20 days. The winter (December to February) planted sugarcane generally takes

70–120 days for germination as the average temperature is low to 11–16 °C. The long germination stage is unsuitable for sugarcane because the seed cane setts in soil are vulnerable to drought, diseases, and pests, especially pineapple and smut diseases. The pathogens of these diseases infect the seed cones from the two cut sides, make the tissues get rotten, and necrotize the buds and root points closed both cut ends, leading to low germination rate. That is why seed cane setts with multiple buds plus watering and plastic film mulching are recommended for winter-planted sugarcane (Li et al. 2000). Seed cane soaking, disinfection, artificially accelerating germination and covering with plastic film, and other measures can increase the temperature and moisture, shorten the germination stage, increase the seedling numbers, and strong culture seedlings.

1.2.2 Water

The germination of the seed cane root points requests higher moisture than that of buds. Insufficient water is not suitable for the germination of both roots and buds of seed cane setts. The water content in seed cane affects the hydrolytic enzymes' activities and the metabolism and transportation of organic substances. The water content in fresh seed cane is generally over 70%, basically meeting the requirement of germination and early growth of young plants. When the water content decreases to 50%, the germination rate decreases significantly; when it goes down to 40% or lower, the buds will lose the germinating ability, and it could not recover even by soaking the seed cane in water (Yang and Li 1995; Li 2010; Verma et al. 2019a).

Soil water content greatly affects seed cane germination. The appropriate soil water content for seed cane germination is 20–30% and best 25%. If the soil water content is over 40%, the germination will be inhibited, and the seed cane setts even get rotten under the long time of waterlogging or flooding conditions. So, field drainage is very important for sugarcane production (Li 2010; Li and Yang 2014). Soil drought might cause the water loss from seed canes which adversely affect the germination of buds and root points. Increasing the water content to 75–80% by soaking or keeping the soil moist (equivalent to 60–70% of field moisture keeping capacity) is recommended so that the seed canes can absorb enough water for root germination. When soil water lowers than 5%, the seed cane planted will be getting dry, leading death of most buds and young shoots. Therefore, keeping the soil moist is the key practice when sugarcane is grown in dry seasons of winter or spring. Experiments showed that leaf-removed multiple-bud seed cane setts germinated better than other seed cane treatments under spring drought conditions, which had higher emergence rate, lower dead seedling rate, higher millable stalks, finally achieving higher cane and sugar productivity (Li et al. 2000). In commercial sugarcane production, if buds germinate while seed roots keep dormant or get the day after germination, it indicates soil moisture is insufficient, and moisture supplement is necessary. Otherwise, seed canes would continuously lose water, leading to bud germination failure or death of germinated buds because of drought stress. Too much soil water is also not good for seed cane germination, and rotten roots and dead buds would occur because of lacking oxygen.

Wang et al. (2008a, b, c) soaked sugarcane seed cane setts with three levels of ethephon (0, 100, 200 ppm) for 10 min before planting for three sugarcane varieties, ROC10, ROC22, GT17. The results showed that, under drought conditions, the plants treated with 100 and 200 mg/L ethephon had higher contents of protein and nucleic acid, the varieties GT17 and ROC10 showed lower protease activity than ROC22, the varieties ROC22 and ROC10 had higher RNA/DNA ratio in roots at 4–5 leaves stage, and the effects were higher in the treatment with 100 mg/L ethephon than in that with 200 mg/L ethephon (Wang et al. 2008a). Water stress led to the considerable amount of accumulation of spermine (Spm), spermidine (Spd), and putrescine (Put) in roots, and the varieties ROC22 and ROC10 accumulated higher polyamine content than GT17. However, they all showed lower polyamine oxidase activity in the treatments with 100 and 200 mg/L ethephon. Meanwhile, the treatments with 100 and 200 mg/L ethephon abbreviated the water potential decrease level in leaves under water stress, and the latter performed better (Wang et al. 2008b). Under water stress, the treatments with 100 and 200 ppm ethephon improved the carotenoid content in leaves of GT17; abbreviated the decreasing of chlorophyll, decreased the stomatal conductance and transpiration rate, and promoted the net photosynthesis in leaves of GT17 and ROC10; promoted the tillering bud formation in the tested three varieties, and the effect was statistically significant in ROC22 and ROC10. These results indicated that ethephon soaking seed cane could improve the drought resistance of sugarcane.

1.2.3 Air

The germination of roots and buds requests good air condition. Under good air conditions, the nutrient inversion inside seed canes acts fast, releasing enough energy and simple organic molecules to ensure normal germination and young shoot growth. In general, upland fields have good air condition, the seed roots can germinate and grow normally except the sugarcane plated in heavy clay soil, or the recovered soil is too thick, or the drainage is poor, which leads to poor air and lacking oxygen condition to inhibit the germination and seedling growth. In sugarcane production, it is important to apply deep tillage and losing soils to create good air condition and keep away from waterlogging after planting and break soil compaction after raining to improve the air condition.

1.3 Seedling Stage

This stage covers the duration from 10% emerged shoots having first true leaf to 50% seedlings having fifth true leaf. The seedling stage is the preparation time for tillering. At this stage, no plant stalk elongates, but leaf number continuously increases, and leaf area keeps enlarging; underground plants roots develop and play roles together with seed roots, so the absorption ability gets stronger; the growth and development of roots and leaves depend on each other; the growth of seedlings becomes utterly independent from supporting by the nutrients from seed cane.

After emergence, the young shoots grow leaf sheath without blade at first, followed by a small complete leaf, the first true leaf. Since then, the following leaves have become larger and larger. When the plants have 3–4 true leaves, roots are generated from the basal node of seedlings, called plant roots stronger than seed roots. When the seedlings have 3–4 leaves, the underground parts start to generate tillering buds. If the plants grow well, they will produce more tillering buds, and oppositely, they will tiller late and less. Ensuring enough number of strong seedlings is the basis of high yield in sugarcane production (Li 2010).

Temperature, moisture, and soil nutrition are the major factors affecting the growth and development of sugarcane seedlings.

1.3.1 Temperature, Moisture, and Nutrition

The starting temperature for seedling growth is 15 °C, and the optimum is about 25 °C. In winter and spring, the seedlings grow slowly because of the relatively low temperature. Entering March and April, the ambient air temperature rises fast, and the seedlings grow faster. In early spring, the air temperature rises faster than the soil temperature, we can promote the seedling growth by appropriate control of moisture and intertillage.

The water requirement is not much at the seedling stage, and it will be good to keep 60% of the soil moisture keeping ability. If the soil water is too much, the air condition is bad, and soil temperature increases slowly, which is not suitable for the growth and development of seedling roots. Intertillage is the common practice to improve the condition for seedling growth and development. If the soil moisture is insufficient, irrigation is strongly recommended to avoid the seedling suffering from drought damage. The nutrients for the early growth of the seedling mainly come from the seed cane. The nutrition requirement of the seedling is less than 1% of the total for its whole growth duration, but it is the critical stage for sugarcane growth. The plant growth is sensitive to fertilization at this stage, and fertilization is usually carried out at the 3–4 leaves stage if the soil nutrition is poor.

1.4 Tillering Stage

This stage covers the duration from starting to ending of tillering when the plant grows less than 3 cm every 10 days, from 10% seedlings having tillers to the beginning of elongation. It is the key stage for ensuring the suitable number of stalks essential for a good yield. The lateral buds on the stem base start germinating when the mother plants have 3–4 true leaves, and the first tiller emerges at the 7–8th leaves stage and the second at the 8–9 leaves stage. The tillering reaches the peak at the 10th leaf stage. The stalk elongation starts after the 12th leaf stage. The late tillering usually could not produce millable stalks, so it should be inhibited.

The tillering ability is closely related to variety, cultivation, and environmental conditions. The main environmental factors affecting tillering include temperature, sunshine, soil moisture, and nutrients.

1.4.1 Temperature, Sunshine, Soil Moisture, and Nutrients

Both air and soil temperatures significantly affect the tillering. The minimum air temperature for tillering is 20 °C, and the optimum is 30 °C. The practices such as plastic film mulching, sallow covered soil layer above seed cane, weeding, intertillage culture operation can promote tillering. However, if the temperature is too high, the tillering will be inhibited. Intense and long sunshine time is beneficial to the generation and growth of tillers because of increasing the air and soil temperature, which would improve the photosynthetic ability, increase organic nutrients, break the hormone balance inside sugarcane, and abbreviate the inhibition of some hormones (mainly auxin, that is, indel acetic acid, IAA) on the lateral buds on the stalk base. Appropriate plant density and weeding should be applied to provide good sunshine to the plants.

The status of soil moisture and nutrient conditions significantly affects the tillering. Sufficient soil water and nutrients promote early and rich tillering. Nitrogen (N), phosphorous (P), and potassium (K) are important to tillering, especially N and P. Insufficient soil sulfur (S), calcium (Ca), magnesium (Mg), and other micronutrients also delay and reduce the tillering. Drought or waterlogging also inhibits the generation and growth of the tillers. It is good for tillering to keep 70% of the moisture keeping compacity in the sugarcane field (Li 2010).

1.5 Elongation Stage

It is also called the grand growth stage, and it is the booming stage for sugarcane growth. This stage starts from the beginning to the end of fast stalk elongation. It is the most important stage for cane productivity formation, which duration is closely related to environmental conditions.

1.5.1 Temperature and Water

The stalk elongation likes warm and strong sunshine. The optimum temperature is about 30 °C, and the elongation is slow at 20 °C and stops below 10 °C. Water condition is highly important to sugarcane stalk elongation. The crop consumes about 50–60% of the total water required for whole life. Drought will greatly reduce the stalk growth, shorten the internode length, and finally decline the cane yield. In upland fields of Southern China, drought occurs frequently, so water management determines the sugarcane productivity. Irrigation is very important when drought comes. In the fields without irrigation conditions, deep tillage and losing soils, sealing the ditch to store water, and mulching soil surface with the trash are the common practices for field management (Li et al. 2016; Li 2019, 2020). Sufficient water can also ensure the nutrient absorption of the plants from the soil and promote nitrogen-fixing activity inside the plants (Li et al. 2016; Li 2019, 2020).

1.6 Maturation Stage

Sugarcane maturation includes two different concepts: processing maturation and physiological maturation.

1.6.1 Processing Maturation

In general, the maturation stage means the processing maturation stage, also called the sugar accumulation stage, which starts in November in subtropical Southern China (Li 2010). During this stage, rapid sugar accumulation happens, and vegetative growth is reduced. As ripening progresses, simple sugars such as fructose glucose are converted into sucrose. Cane ripening starts from bottom to top, and therefore bottom part of the cane contains more sugars than the top portions at the early maturation stage. Sugarcane stalks account for about 75% at the harvest stage, while the leaves and tops around 25% of the total aboveground dry biomass (Li 2010). Different sugarcane varieties have different sucrose content in cane and different maturation times.

The main environmental factors affecting sugar accumulation in sugarcane are temperature and water.

1. **Temperature**
   The processing maturation requests cool temperature relatively big temperature difference between day and night. The best temperature for sugar accumulation is 13–18 °C on average for the day and 5–7 °C for the night, with about 10 °C difference between day and night. High temperature is good for growth but not suitable for sugar accumulation in sugarcane. The environment with relatively low temperature, dry air, and the big temperature difference is beneficial to ripening and accumulating sugar in the stalks of sugarcane during the late growth stage. On the contrary, wet and warm environment with the slight temperature difference between day and night is not good for sugar accumulation in sugarcane.
2. **Water**
   Rainy and wet environment is beneficial to plant growth but leads to late ripening and low sugar content. In Southern China, the rainfall in September and October is closely related to cane sucrose content in November. If the rainfall is low in September and October, the sucrose content in cane will be high in November,

and frequent raining will decrease the sucrose content in cane. So irrigation should be reduced since late September and stopped in a month before harvest. But over drought also adversely affects the sugar accumulation and leads to high colloid content in cane juice (Li 2010; Yang et al. 1998; Verma et al. 2019b). Under drought conditions, appropriate irrigation is strongly recommended to improve yield and sucrose content in cane.

3. **Nutrients**
   Over and/or late application of N fertilizer will decrease sucrose content in cane. In Guangxi, China, stopping the application of N fertilizer in May recorded the highest sucrose content in cane and sugar productivity (Ye et al. 1993). For different sugarcane varieties, those with lower N content in leaves, especially at the late growth stage, mature earlier and have higher sucrose content in cane (Li et al. 1992). Phosphorus and potassium supplements at the late growth stage are beneficial to sugar accumulation in sugarcane. Experiments showed that foliar spray of limewater and KH_2PO_4 increased the activities of Mg^{2+}-ATPase, Ca^{2+}-ATPase, NADP-malic enzyme and neutral invertase and the contents of sucrose and water in leaves and improved the sucrose content in cane while reduced the reducing sugar content in juice and increased cane yield in plant cane (Li and Yang 1994). Similar results were obtained in ratoon cane (Yang et al. 1998).

1.7 Physiological Maturation

Sugarcane plants will flow and seed under the comprehensive effect of appropriate light, temperature, and water, reaching physiological maturation. Flowering is necessary for sugarcane hybrid breeding. Sugarcane is easy to flower in lower latitude areas in the tropics, with low temperature and humidity and is not suitable for sugarcane flowering and seedling. It is common to increase the air temperature and humidity in the greenhouse (Li 2010).

1.8 Conclusion

Due to the good economic return to the growers, the area and productivity of sugarcane have constantly been rising over the last few years. Sugarcane is a warm-temperate and (semi) arid crop that grows in a warm, sunshine, and wet environment, as well as fertile, deep, and well-aerated soils. Climate variables influence the crop cycle, development, and ripening: precipitation and temperature stimulate growth, whereas dry, sunny days, and low night temperatures support developmental processes and sugar accumulation. Cold and storms or typhoons can damage the crop. In temperate regions, new modern varieties have been explored which are adapted to a shorter growth cycle.

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