Cultivated sugarcane (*Saccharum* sp.) is a vegetatively propagated, perennial grass that originated in Northern India and New Guinea (Grassl, 1977). Most cultivars are complex tri-species hybrids adapted to tropical and subtropical climates. The soft, juicy stems contain 9 to 15% sucrose on a fresh weight basis. The juice is extracted by milling, evaporated, and the resulting crystalline sucrose is termed raw sugar. The familiar white sugar is obtained by further refining of raw sugar. In some countries, crude sugar products are prepared by boiling juice in open pans.

I. PARENTAL MATERIAL

Grassl (1977) considers that the genus *Saccharum* consists of four species: *S. officinarum* L., *S. spontaneum* L., *S. robustum* Brandes and Jeswiet ex Grassl, and *S. sanguineum* (Grassl) Grassl. He suggested referring to the formerly recognized species *S. sinense*, *S. barberi*, and *S. edule* as horticultural groups derived from natural intergeneric hybridization. Controversy exists about the taxonomy of the genus and additional data are needed before agreement is achieved (Daniels et al., 1975).

*Saccharum officinarum* (2n=80) is characterized by large, juicy stalks with high sugar content, disease susceptibility, and low vigor. These clones and their natural hybrids were grown commercially for centuries until hybridization work began in the late 19th century. *Saccharum spontaneum* (2n=40 to 128) and groups Sinense (2n=118) and Barberi (2n=82 to 124) are characterized by thin stalks with high fiber and low sugar content, disease resistance, vigor, and cold tolerance. *Saccharum robustum* (2n=60 to 194) clones often have very large stalks, low sugar content, leaves that shed at maturity, and adaptability to wet conditions. *Saccharum sanguineum* (2n=60), formerly included in *S. robustum*, has red interior stalk color.
Group Edule produces an edible inflorescence, often with abortive flower parts, that does not emerge from the enclosing leaf sheath and, therefore, cannot be hybridized.

Early sugarcane breeders achieved great success through interspecific hybridization, particularly in obtaining resistance to diseases, cold tolerance, and increased vigor. Because sugarcane is vegetatively propagated, the genetic constitution of the derived hybrids is fixed, and these hybrids could be grown commercially without developing pure lines. Most commercial cultivars today can be traced to the early hybridization work in Java and Coimbatore, India (Jeswiet, 1927a, Dutt et al., 1953). The species involved were S. officinarum, S. spontaneum, and horticultural group Barberi. Later, horticultural group Sinense and then S. robustum were included in breeding schemes.

Clones of the genus Saccharum were hybridized with at least the following seven genera: Eccoilopus, Miscanthidium, Miscanthus, Ripidium, Sclerostachya, Sorghum and Zea. Grassl (1977) speculates that this number may be increased to 20 as other genera become available.

A World Germplasm Collection of sugarcane is maintained by the Science and Education Administration-U.S. Department of Agriculture (SEA-USDA) at Beltsville, Md., and Canal Point, Fla., and by the Sugarcane Breeding Institute at Cannanore, India (Anonymous, 1971). These duplicate collections are maintained under the auspices of the International Society of Sugar Cane technologists and contain 1,200 to 1,800 representatives of Saccharum, horticultural groups, and related genera.

II. PLANT CULTURE

A. Field

Sugarcane is usually grown for hybridization in one to three-row plots 3 to 20 m in length with row spacings of 3 to 6 m to permit accessibility to flowering plants by people or vehicles. With few exceptions, flowering stalks are moved from the field to a central location for hybridization. Plantings generally are made in the fall of the year for use during the next flowering season. Stalks are cut into three-bud pieces, dropped in furrows at the rate of about 14 buds/m of row, and covered with 5 to 20 cm of soil. In some areas, fungicide treatment is applied to seed pieces at or before planting to control diseases. Fertilization is often less than that recommended for commercial culture to reduce lodging and assure low nutritional status during the period of floral initiation. The usual practice is to harvest the stalks after the flowering season and allow the planting to ratoon for an additional 1 to 5 years (Heinz, 1977; Miller, 1977).

At some locations where lodging is a serious problem, such as Canal Point, Fla., plots are about 3 m long, so that rope or nylon strapping can be interlaced among stalks and tied to posts placed at both ends of plots to prevent lodging (Duncikelman, 1959). In some hybridization programs at high latitudes, natural flowering in the field rarely occurs because of a limited number of daily photoinductive cycles or low temperature. In such cases, field plantings may serve only as a source of cuttings to plant in pots or cans in a greenhouse.
Clements and Awada (1965) and Coleman (1968) discussed factors that influence flowering of sugarcane and outlined the following optimum conditions for floral induction: a plant that has two to four elongated internodes exposed; photoperiod of 12 hours 16 min to 12 hours 26 min with high light level; day temperature of 26.7 to 30.6 °C; night temperature of 21.7 to 23.2 °C; vigorous plant cane (first year crop), but changing to a low nutritional status; and low soil moisture tension. In the Northern Hemisphere, floral initiation occurs from mid-August to mid-October and flowers emerge from mid-November to mid-January or later (James and Miller, 1971). Some S. spontaneum clones have different photoperiod requirements and as a group flower from early spring until late winter.

B. Growth Chamber and Greenhouse

Sugarcane is grown in pot cultures at all latitudes for photoinduction experiments and for all hybridization work at high latitudes where natural flowering rarely occurs in the field because of low temperatures. When temperatures can be less than 21 °C, plants in pot cultures are left outside during the day and moved into heated greenhouses or photoinduction chambers at night (Fig. 1 and 2) (James, 1968; Palisateas, 1962).

At Canal Point, Fla., single-bud seed pieces of chosen parental clones are planted upright in greenhouse flats filled with muck soil in February each year (James, 1968). In early April, the young plants are transplanted to 38-liter cans in a mixture of sand and muck soil. Cans of female parents are placed adjacent to outside racks equipped with tie bars to which developing stalks are tied to prevent lodging. A watering system constructed of plastic pipe fitted with nozzles provides an efficient means of watering plants during the growing season. Cans of male parents are placed on rail carts that can be moved into a heated crossing house at night to protect plants when temperature drops below 21 °C during fall and winter (Fig. 1). Plants are fertilized at 3-week intervals from April to July, then fertilization is discontinued until October to assure low nutritional status during the floral initiation period in September. Various schemes were devised for managing plants in pot cultures, but the essential features are a potting medium that permits adequate drainage, proper fertilization, adequate water, and a method to prevent lodging as stalks elongate.

III. FLORAL CHARACTERISTICS

The inflorescence of sugarcane, referred to as an arrow or tassel, is an open panicle with main axis and lateral axes of first, second, and third orders (Artschwager et al., 1929). Branching is greatest at the lower end of the panicle and decreases in an apical direction (Fig. 3). Four to 100,000 or more spikelets occur in pairs alternately at rachis nodes. One spikelet of each pair is sessile and the other pedicellate (Fig. 4). Long, silky callus hairs are attached to the base of each spikelet. At maturity, the lateral axes of the inflorescence break below the spikelets at rachis nodes. The pedicellate spikelet breaks free, leaving the sessile spikelet attached to the rachis segment and the stalk of the pedicellate spikelet (Fig. 4).
Fig. 1—Sugarcane crossing house at Canal Point, Fla., showing rail carts for transporting male parents to the heated crossing house. The lighting system on the left is used to delay flowering. Tie bars between posts are used to support sugarcane stalks as they elongate during the growing season.

Fig. 2—Interior of crossing house at Canal Point, Fla., showing isolation cubicles. Sugarcane panicles that were bagged to save the first seeds to ripen are shown in the upper left-hand corner.
Fig. 3—Inflorescence of sugarcane.
Each spikelet contains a single flower consisting of three or four glumes, two lodicules, a whorl of three stamens, and a single ovary with two feathery, purple stigmas. Flowers that are about to open can be recognized by stigmas protruding from the closed glumes. As anthesis approaches, the filaments lengthen and the anthers are extruded. Often the flowers are imperfect with only rudimentary development of the ovary or with anthers devoid of pollen grains.

The sugarcane caryopsis is typical of grasses and remains enclosed in the glumes at maturity with stigmas attached (Fig. 4).

As the plant develops, internodes and leaf sheaths below the apical region become successively longer while leaf blades become successively shorter. The uppermost leaf consists of a sheath about 1 m long, fully enclosing the young panicle, with a blade only about 15 cm in length. This is known as the flag or boenting stage. Elongation of the peduncle causes emergence of the inflorescence. After emergence is complete, the panicle is well above the leaf canopy at a height of 3 to 6 m from the ground and in position for wind pollination to occur.

Anthesis may begin as the inflorescence starts to emerge from the flag leaf or as much as several days after full emergence. In all clones, anthesis takes place from the top of the panicle downward and from the ends of panicle branches inward. Some flowers usually open before sunrise each day, and the process is completed in 3 to 14 days. Following the opening of
the flower, anther dehiscence usually takes place after some drying has occurred, if the humidity is high. Fertile anthers split along the antherior walls one-quarter to one-half the length of the anther from top to bottom to release pollen.

Stigmas are receptive when flowers open (Artschwager et al., 1929). Wind and humidity probably affect length of the receptive period because stigmas protrude from glumes. There has been little need to determine the period of receptivity because of the hybridization techniques that are employed throughout the world.

Degree of anther dehiscence and pollen viability ranges from 0 to 100% among sugarcane clones. Few complex species hybrids are completely male-sterile, and breeders must classify intended parental clones for use as male parents or female parents when making biparental crosses. This is usually based on percentage of anthers that dehisce and the percentage of released pollen that is viable as determined by the starch test (Van-Breemen et al., 1962), vital stains, or occasionally by germination of pollen (Moore and Jung, 1974).

Pollen germinates immediately after falling on the stigmatic papilla. The pollen tube grows down the style and enters the ovary (Artschwager et al., 1929). The fertilization process was not observed, but fertilization is considered to take place within 8 hours after pollination because fertilized egg sacs were detected within about 7 hours (Bremer, 1959; Dutt and Rao, 1933).

IV. ARTIFICIAL HYBRIDIZATION AND SELF-POLLINATION

A. Equipment

Facilities and methods required for a successful hybridization program with sugarcane are determined largely by the latitude where the work is undertaken. In more tropical climates between approximately 20° North and South latitudes, temperature is generally favorable for flowering and pollen fertility. Hybridization can be conducted in the open, usually among trees or other windbreaks, and sometimes under temporary or permanent shelters to protect inflorescences from wind and rain. The inflorescences are susceptible to breakage from high winds, particularly when laden with moisture.

At high latitudes, low temperature during the fall and winter adversely affects pollen fertility and depresses flowering (Brett, 1950). Heated greenhouses are required to protect at least the male parents during flower development and hybridization. Photoperiod houses may be required to induce flowering and thereby extend the range of parental clones available for hybridization.

At even higher latitudes where natural flowering rarely occurs, both male and female parents must be protected from low temperature by placing them in heated greenhouses. The restricted natural flowering may necessitate extensive photoperiod facilities for induction of most, if not all, parental clones. Because sugarcane is vegetatively propagated, all plants
subjected to selection are derived directly from seed obtained by hybridization, and demands on hybridization programs range from several thousand to 2 million or more seeds each year. Other equipment depends on the method selected for maintaining the male and female parents during pollination and seed maturation.

B. Preparation of the Female

Sugarcane breeders in Barbados initially emasculated the small sugarcane flowers with the aid of a dissecting microscope while working in the field on platforms about 3 m above the ground. This practice was soon abandoned in favor of selecting female parents that were highly male-sterile. Various emasculation techniques were tried such as the use of suction, hot water, chemicals, and high humidity to prevent anther dehiscence (Stevenson, 1965). Low temperature during flower development at least partially destroys pollen viability and has been used to emasculate male-fertile clones by growing them outside in subtropical climates (Dunckelman, 1959) or placing them in cold rooms at 15 C during late stages of flower development (Paliatsas, 1977). A satisfactory emasculation technique is not yet available and, with few exceptions, sugarcane breeders select clones for female parents that are partially or highly male-sterile. In Barbados and other locations, portable enclosures (lanterns) were developed that could be placed over female inflorescences in the field to provide isolation from foreign pollen (Stevenson, 1965).

A marcotting (air-layering) method was developed in India that permitted isolation of field-grown flowering stalks of both male and female parents (Venkatrama and Thomas, 1926). At least several weeks before flowers emerged, two halves of a clay pot were tied in place around a stalk so that one or two root bands near the nodes of the stalk were covered when the pot was filled with moist soil or other rooting medium. After a few weeks, a root system developed from the root primordia in the root band. The stalks were cut below the pot either before or after flower emergence, transported to an isolated area, and hybridized under temporary crossing sheds (Sahib et al., 1927).

The marcotting technique was modified later by replacing pots with stove pipes (Paliatsas et al., 1953). Finally, plastic film was used to enclose sphagnum moss or other rooting medium (Dutt and Hussainy, 1956).

In Hawaii, Verret (1925) discovered that cut stalks would live for several days or weeks and many would develop mature seed when the cut ends were immersed in a 500 ppm sulfuric acid solution. The acid solution was modified later to include phosphoric acid (Mangelsdorf, 1953) and still later to include sulfuric and nitric acids (Warner, 1961). The present recommended solution consists of 150 ppm sulfuric acid + 75 ppm phosphoric acid + 37.5 ppm sulfuric acid + 37.5 ppm nitric acid (Heinz, 1977). Solutions are usually changed occasionally and replenished with fresh solutions or acid stock. In some programs, an internode is cut from the base of stalks one or two times during the period stalks are in solution. Rubber or plastic containers are used in preference to metal containers to prevent neutralization of the acid.
Over the years, the solution method for maintaining female parents was adopted by many sugarcane breeders. At some locations, it was necessary to use rainwater (Stevenson, 1965) or deionized water (James, 1968) to make the solution, particularly when water from the normal source was highly alkaline. The advantage of the solution method is that neither male nor female parents require prior preparation. Labor costs are reduced and all inflorescences that emerge can be hybridized. The flowering stalks are simply cut at the proper time after flower emergence and moved to the hybridization area.

C. Pollination

In the early years of hybridization, male parents had to be replaced each day because a method to keep them alive was not available. Much of this work was done at night to have the male parents in place when female flowers opened about sunrise (Jeswiet, 1927b; Stevenson, 1965).

With development of the marcotting and solution techniques, it was no longer necessary to replace male parents each day. Typical pollination procedures now consist of cutting both male and female flowering stalks as anthesis begins and moving them to a crossing shelter where they are placed together in a crossing lantern or cubicule (Fig. 2 and 5). Male flowering stalks are shaken each morning at about 0800 hours to dislodge pollen. After 10 to 14 days, male parents are discarded and female parents are retained an additional 10 to 20 days until seed is ripe.

In Hawaii, the Experiment Station of the Hawaiian Sugar Planters Association conducts an extensive hybridization program under tropical conditions (Heinz, 1977). Two types of crosses are made: biparental, in

Fig. 5—Crossing shelter at Maunawili, Hawaii, showing lanterns for biparental sugarcane crosses. (Photo courtesy D. J. Heinz, Hawaiian Sugar Planters Association).
which one male parent and one highly male-sterile female parent are placed together in a lantern for isolation (Fig. 5), and melting pot (modified polycross) in which several elite male parents and a large number of female parents are placed together under a crossing shelter. Stalks are held upright by inserting them through large mesh wire suspended in a horizontal position about 1 m above the ground. The cut ends are placed in solution containers. Solutions are changed twice weekly and replenished on intervening days. Male parents in biparental crosses are discarded after 10 to 12 days, but male parents are retained in melting pot crosses and all seed is harvested when ripe.

At Canal Point, Fla., the SEA-USDA conducts a hybridization program in a large plastic-covered crossing house (ca. 61 m long × 9 m wide × 7 m high) in which temperature is maintained above 21°C (Fig. 1). Cubicles on each side of the house provide isolation from foreign pollen (Fig. 2). Either the marcott or solution technique is used to maintain both male and female parents during hybridization. When stalks are marcotted, male parents are cut below the rooted section as anthesis begins, leaf blades are removed, and the stalks are carried to the crossing house. The enclosing leaf sheath is removed to completely expose the panicle. The stalks are tied to support bars with the rooted section suspended in the air. Plastic bags are placed over the rooted sections, tied to stalks, and filled with water to keep the stalks alive. Female parents are cut and prepared for crossing in the same manner as male parents. Rooted sections are placed in troughs of tap water that is circulated and aerated by continuous pumping.

For the solution technique, cut ends of stalks from the male parents are placed in 1-liter jars containing a weak acid solution. The jars are tied to the stalks and the stalks are tied to the support bars in cubicles with the jars suspended in the air. Cut ends of stalks from the female parents are placed in rubber tubs containing a weak acid solution.

Height of male panicles for both the marcott and solution techniques is adjusted so that they will be about 0.3 m above female panicles. All female stalks are tied to the same support bars as the male parents to keep them upright. Usually one male parent and several female parents are placed in a cubicle. At 0800 hours each morning, the support bars are shaken to disperse pollen. Male parents are discarded after a 10 to 14-day pollination period, and female parents are retained until seed is ripe.

D. Factors Affecting Efficiency

Several approaches have been used to alter flowering dates, such as time of planting (Stevenson, 1965), growing parental clones at different elevations (Van-Breemen et al., 1962) and on different soil types (Grassl and Belcher, 1953), and leaf trimming and chemical sprays (Buzacott, 1959).

Most research to alter time of flowering has dealt with manipulation of photoperiod. Researchers generally have attempted to induce earlier flowering by decreasing the natural photoperiod during the summer (Chilton and Paliatsias, 1956; Paliatsias, 1962; James and Miller, 1971). Others have attempted to delay flowering of early-flowering clones by interrupting the dark period with light to delay floral initiation and subsequent flowering.
SUGARCANE

(Coleman, 1962; Moore and Heinz, 1971; James, 1972). More recently, extension of the photoperiod after floral initiation occurred naturally was shown to delay flowering by as much as 3 months (James and Miller, 1971; Moore and Heinz, 1971).

With proper application of current technology, sugarcane breeders can synchronize flowering of most clones, except those of S. officinarum. There is great variation in specific photoperiod requirements among Saccharum clones, and sugarcane breeders must determine the exact requirements for asynchronous and non-flowering clones that are chosen for hybridization.

The method selected for maintaining female stalks influences seed set, at least in some years. For example, at Canal Point, Fla., seed set for the weak acid solution method was only 60 to 92% as high as for the marcottage method (Miller, 1977). Selection of strong pollen producers as male parents increases seed set, but in most programs it is necessary to use weak pollen producers as male parents to utilize a wide range of germplasm. Seed set is extremely variable and ranges from 0 to 5,000 or more viable seed from one inflorescence. Average seed set per inflorescence was 520 for a 9-year period at Canal Point and ranged from 214 to 774 (James and Miller, 1973). Average seed set above 1,000 per inflorescence is unusual (Palatineas, 1977).

V. NATURAL HYBRIDIZATION

Natural hybridization is not an important technique in sugarcane. Polycross blocks occasionally are established in the field, but asynchronous flowering within as well as among clones reduces the effectiveness of the method.

VI. SEED DEVELOPMENT, HARVEST, AND STORAGE

Seed maturity in sugarcane follows the same pattern as anthesis. Ripening of seeds begins at the top of the panicle and proceeds downward to the base. The minimum length of time from the beginning of the pollination period to seed maturity is about 22 days (Heinz, 1977). As the inflorescence begins to disintegrate, the ripe seeds at the top are lost before seeds at the base are mature. In some programs, panicles are harvested 22 to 36 days from the beginning of the pollination period after one-third of the seed has fallen (Heinz, 1977).

Stevenson (1963) described a method used in Barbados of taping paper cones around and below panicles to catch the first seeds to ripen and fall. At Canal Point, Dunckelman (1963) enclosed panicles in lightweight paper clothing bags and increased seed production by 50% when panicles were harvested at 30 to 36 days after the beginning of pollination compared to harvesting when the first seeds began to fall. Currently, panicles are bagged about 20 days after pollination begins. Panicles of flowering stalks maintained in weak acid solution are harvested 10 days after they are bagged and those of marcotted stalks 14 to 16 days after they are bagged.
At harvest, peduncles are cut below the panicles and the bagged panicles are dried in a forced air oven at 29 to 40 C until spikelets can be hand-stripped from panicle branches, usually 2 or 3 days. Seeds are placed in kraft paper or plastic bags. Bags are weighed and identified by year, cross number, and parentage. Seeds are either planted immediately or stored at temperatures ranging from −10 to −30 C (Heinz, 1977; Miller, 1977). At Canal Point, a 1-g random sample is obtained from each cross for germination tests before planting or storage to estimate seed production and to determine the proper planting rate in greenhouse flats.

Sugarcane seed (fuzz), being a mass of spikelets with callus hairs attached, is difficult to plant evenly in flats. Various methods were tried to remove callus hairs, such as use of sulfuric acid and burning and rubbing. A procedure utilizing a rice scarifier has now been developed that seems to be both effective and efficient (Breaux, 1977).

REFERENCES


Heinz, D. J. 1977. Personal communication. Experiment Station, Hawaiian Sugar Planters Association, P.O. Box 1057, Aiea, HI 96701.


Miller, J. D. 1977. Personal communications. Sugarcane Field Station, Star Route Box 8, Canal Point, FL 33438.


