Sorghum, *Sorghum bicolor* (L.) Moench, is a major food and feed grain crop, and its vegetative parts are used as forage, syrup, and shelter. Of tropical origin, sorghum is grown extensively in marginal rainfall areas of the tropics and subtropics, and has been adapted to and is widely grown in temperate climates.

1. **PARENTAL MATERIAL**

Cultivated sorghum consists of several morphologically distinct races which can be readily crossed. Although most scientists now consider all of these types as a single species, many older reports treat the types within *S. bicolor* (formerly called *S. vulgare* Pers.) as distinct species, and one must interpret the literature with discretion.

Several grassy types, e.g., *S. arundinaceum*, *verticilliflorum*, and *aethiopicum*, with the same chromosome number as *S. bicolor* (2N = 20), can be crossed with *S. bicolor* with only slight barriers to gene exchange. These types usually are considered to be species different from *S. bicolor*. Sudangrass, sometimes called *S. sudanense*, is fully compatible with and is usually considered to be a variety of *S. bicolor*.
The subsection Halepense, typified by Johnsongrass, *S. halepense*, contains species which are related to *S. bicolor* and have a chromosome number of 2N = 40, except for *S. propinquum* which has 2N = 20. Other groups (Parasorghum, Stiposorghum, Chaetosorghum, and Heterosorghum) have chromosomes that are morphologically distinct from those of the species previously discussed and have never been successfully crossed with those species. Classifications and species relations are discussed in several reports (Harlan and de Wet, 1972; Celarier, 1958). Sorghum has been crossed with sugarcane (*Saccharum*) (Thomas and Venkatraman, 1930), and it has also been indicated that sorghum and *Zea mays* have been successfully crossed (James, 1976).

The collection, assembly, and classification of sorghum entries into a World Collection by K. Rachie and associates provided the material for expanded germplasm introduction (Murty et al., 1967). A sorghum conversion program was initiated by the U.S. Department of Agriculture and the Texas Agricultural Experiment Station using the assembled lines of the World Collection (Stephens et al., 1967). Many photoperiod-sensitive (short day) lines have been converted to temperate adaptation by this and other similar backcrossing programs and will flower and set seed in long days. As a result, many diverse types are available for breeding programs throughout the world. The World Collection is being maintained at the International Crops Research Institute for Semi-Arid Tropics (ICRISAT) at Hyderabad, India and a large part of it is in long-term storage at the USDA National Seed Storage Laboratory, Fort Collins, Colo.

**II. PLANT CULTURE**

**A. Field**

Sorghum grows well in soils of many different types when other environmental conditions are suitable. Recommended fertilization practices depend on soil, climatic, and past cropping variables (Ross and Webster, 1964).

Adequate moisture is needed for maximum production and should always be available at heading and flowering. Sorghum can, however, tolerate rather dry conditions. It has the ability to slow its growth during a dry period and resume development when conditions improve. Cultivars differ considerably in their reaction to moisture stress, and those that would ordinarily flower at the same time may differ in flowering date after an extended dry period. High humidity and early morning dews will delay flowering on specific days, and little or no flowering occurs during a cool, rainy day.

The efficiency of a sorghum hybridization program is enhanced by winter nurseries which can be used effectively for making crosses or growing progeny. Plants, however, are usually smaller than normal, with fewer seed per panicle, and selection for productivity potential may not be reliable. Unusual disease or insect problems may affect unadapted material in a winter nursery; one should avoid eliminating germplasm simply because of its response in that nursery. If the weather is too cool, plant development
might be delayed and might cause "blasting" (incomplete development of some spikelets). A distinct advantage of winter nurseries, in addition to the opportunity to obtain another generation, is that photoperiod-sensitive and nonsensitive types will flower at the same time and crosses can be made between them. Such crosses are difficult to make in long summer days because of different flowering responses. To accomplish such crosses in the summer, it is frequently necessary to induce flowering in the photoperiod-sensitive types by excluding light from them for all but 10 hours on 14 consecutive days.

B. Growth Chamber and Greenhouse

Greenhouses are useful for sorghum hybridization. Careful attention to watering, nutrition, and pest control is required. Various potting media may be used, including a light soil or a peat and perlite mixture. Care should be taken not to allow the potting medium to become alkaline or too acidic because micronutrient deficiencies will likely result. Constant temperatures of about 26°C are effective, but day temperatures of 26 to 32°C and night temperatures of 17 to 22°C are especially conducive to good plant growth and development of large panicles. Supplemental light is usually not needed to grow sorghum in greenhouses, but requirements depend on the locality and climate. Although growth chambers have been used for growing sorghum, they are rarely used for hybridization purposes. This is because inconsistent, and frequently discouraging, results have been obtained in attempts to grow sorghum to maturity in growth chambers where light quality and level and temperature requirements are more difficult to satisfy than in greenhouses. Sorghum has been induced to flower in growth chambers at 27°C day/22°C night with about one-half the light level of full sunlight (Eastin, 1976).

III. FLORAL CHARACTERISTICS

Sorghum is mainly self-fertilized with cross-pollination ranging from 2 to 35% and averaging about 6%. Wind and convection currents are the chief agents for pollen movement.

The inflorescence of sorghum is a panicle that varies morphologically from compact to open (Fig. 1). The spikelets are usually in pairs on the branches, one being sessile and fertile and the other being pedicelled and male or sterile (Fig. 2, 3). The terminal sessile spikelet of each branch has two pedicelled spikelets associated with it. The glumes of the fertile sessile spikelet enclose two florets, the upper being perfect and fertile, and the lower being sterile. The fertile floret has a membranous lemma, a palea, two lodicules, three stamens, and an ovary with two long styles with plumose stigmas (Doggett, 1970; Freeman, 1970).

The process of blooming, stigma receptivity, dehiscence of pollen, and fertilization have been reviewed in detail (Stephens and Quinby, 1934; Doggett, 1970). The essential features are that flowering begins 0 to 3 days after panicle emerges from the boot. It begins at or near the panicle apex and proceeds downward for a period of 4 to 7 days. Stigmas are receptive 0 to 2 days before blooming and if unpollinated remain receptive for 5 to 16
days after anthesis, depending on the environment. Anthesis generally occurs in the morning, depending on the cultivar and environment, but has been noted as early as 2200 hours (Stephens and Quinby, 1934). Cool, wet conditions delay flowering. Viable pollen is shed from the anthers until about noon of calm days, but pollen may be all dislodged earlier on windy days. Pollen is generally highly functional for about 30 min after dehiscence and decreases to negligible viability at about 4 hours (Stephens and Quinby, 1934). Environmental conditions such as temperature and humidity affect the duration of viability. Pollen kept under refrigeration is capable of fertilization for 3 to 4 days (Ayyangar and Rao, 1936; Sanchez and Smeltzer, 1965). Sorghum pollen is reported to require light and to germinate only after daybreak (Artschwager and McGuire, 1949). Other requirements being satisfied, pollen germinates when in contact with a receptive stigma, and fertilization usually takes place in about 2 hours. Organ differentiation occurs during the following 12 days, and the embryo continues to grow until the seed is mature. Cultivar differences have been found for stigma receptivity, order of stigma and anther emergence, pollen dehiscence, and flowering response to wet, cool conditions.

Sorghum is a short-day species sensitive to changes of day length. It is a warm season crop with a minimum of 7 to 10 C for germination of seed and 21 C for plant growth (Leonard and Martin, 1963). Optimum temperatures
Fig. 3—Panicle branch of fertile plant. A) Sessile spikelet, B) pedicelled spikelet. 

Fig. 4—Panicle branch of a cytoplasmic-genetic male-sterile plant. 

Fig. 5—Plastic sleeve for hot-water emasculation. 

Fig. 6—Hand emasculation. A) Anthers, B) palea, C) glumes, D) emasculating instrument. Adapted from Poehlman (1977). 

Fig. 7—Panicle ready for pollination after dehiscence control by use of a polyethylene bag.
for sorghum flowering seem to be between 21 and 35 C, and flowering is delayed by temperatures outside of this range. When temperatures drop below 12 C at night, flowering is limited the following day, even at optimum temperatures. Warm nights have a tendency to shorten the growing period of cultivars that are late maturing under other conditions. Each cultivar has a characteristic flowering response at specific planting dates and locations.

IV. ARTIFICIAL HYBRIDIZATION AND SELF-POLLINATION

A. Equipment

A diversity of procedures is used to prepare the female parent for crossing, depending on the pollen control method employed. Equipment needed includes paper pollinating bags of approximately 6 x 12 x 40 cm, smaller bags made of paper, parchment, or dialyzing tubing of approximately 5 x 10 cm dimensions, pollinating aprons, stapler, knives, marking pencils, forceps, clips, small scissors, hot water storage container, thermometer, plastic or rubber sleeve, support for sleeve, polyethylene bags, and string. The first four items can be purchased from suppliers of pollinating or scientific equipment, whereas the others are available at local grocery, stationery, or hardware stores.

B. Preparation of the Female

Pollen control in this perfect-flowered species may be obtained by any of four general methods: male sterility, hot-water emasculation, hand emasculation, and control of anther dehiscence. Preparation of the female varies, depending on the pollen control method used.

Male sterility, genetic or cytoplasmic-genetic (Fig. 4), is the preferred method of pollen control because it takes little time to prepare the female parent and an abundance of hybrid seed can be obtained from a single pollination. Male-sterile plants are selected just before anthesis, and the entire panicle is covered with a paper bag which is stapled or clipped at its base. If anthesis has begun, the opened spikelets are removed with a knife or scissors before the panicle is bagged. Panicles of similar maturity are bagged on any one day so that the bagging date written on the bag can be used to determine when the panicle is ready to pollinate. Covering panicles of unpollinated male-sterile plants with distinctly colored bags facilitates distinguishing them from pollinated panicles of the same plot.

Hot-water emasculation is effective when a large number of seed of a specific hybrid are desired, but male-steriles are not available in the intended female and a few selves would not be objectionable. This method developed by Stephens and Quinby (1933) is employed today with only minor modifications. A panicle that has just begun to flower is chosen and opened spikelets are removed. The panicle is then enclosed in a sleeve of rubber or plastic which is tied tightly around the peduncle and open at the top (Fig. 5). The panicle is covered for 10 min with water at 47 to 48 C. Some cultivars require slightly different maximum temperatures to kill the pollen, but not the ovaries. It is quite simple in the greenhouse to immerse a
panicle in hot water by inverting the potted plant. After treatment with hot water, the panicle is covered with a paper pollinating bag, usually after the panicle has dried somewhat. The identity of the emasculated panicle is provided by a note on the bag or by a bag of distinctive color. A check on the effectiveness of the hot water treatment can be determined by covering and not pollinating one branch of the panicle.

*Hand emasculcation* is used when male sterility is either unavailable or undesirable, when a small quantity of seed is needed, and when selfing cannot be tolerated because it would be impossible to distinguish hybrids from selves. Hand emasculation, however, takes special skill and is time consuming, so it is used only when more rapid methods do not suffice.

Florets are emasculated the day before anthesis. Florets below and within about 3 cm of opened florets usually will open the next day (Fig. 3). Hand emasculations in the field are usually made in the afternoon to avoid contamination by viable pollen from other plants. All open spikelets are removed with scissors, and viable pollen is rinsed from the panicle with water. If there is viable pollen on the hands, scissors, or emasculating tool, they too are rinsed. In most greenhouses, emasculations may be made at any time of the day because air movement is minimal, but rinsing should always be practiced because pollen may remain viable for extended periods in the greenhouse.

Any of three basic instruments are used for hand emasculations. Some workers remove the anthers with a pointed instrument such as a sharpened pencil or a stick of approximately the same dimensions. The point is entered between the outer glumes of the sessile spikelet and the anthers are teased out (Fig. 6). Others use a forceps, usually with flat, broad points, to enter the spikelets and to lightly tease out the anthers. It helps when using either of these instruments to pull one of the glumes partially away from the other to provide room for manipulation of the instrument. Extreme care must be taken to avoid damage to anthers because of selfing which may occur from the released pollen. If an anther is broken or punctured, that spikelet or its ovary is removed and the pollen is removed from the emasculating instrument. The third instrument used is a scissors with which the top one-third of the spikelet and a portion of the anthers are removed (Crook et al., 1972).

Male-fertile, pedicelled spikelets are removed with a forceps or scissors to prevent selfing and to mark emasculated spikelets. Unemasculated spikelets in the region of those emasculated are removed, and a small bag made of paper, parchment, or dialyzing tubing is placed over the emasculated florets, folded, and clipped into place.

*Control of anther dehiscence* by humidity is used to limit self-fertilization of intended female plants when 1) many seeds are desired, and 2) plants derived from selfing can be distinguished from hybrids. In areas of very high humidity, a paper bag placed over a panicle will delay anther dehiscence about 30 min the next morning, which is sufficient time to pollinate it by the ‘pour’ method (Quinby, 1965).

Polyethylene bags may be similarly used to control dehiscence by high humidity for an extended period each day, so many plants can be pollinated (Schertz and Clark, 1967). Panicles that have just begun to flower are chosen and opened spikelets are removed. A polyethylene bag may be placed over the panicle at any time of day and tightly secured around the
peduncle with a string or rubber band. Panicles prepared for crossing are easily identified by the attached polyethylene bag which is left on the panicle for successive days until the desired number of spikelets have opened (Fig. 7). If conditions are hot and calm, however, temperature under the bag may be high enough to injure the flowers. In such cases, one must bag the panicle late in the day, cover the polyethylene bag with a paper bag, pollinate the next day, and remove the unopened spikelets at the base of the panicle. By using polyethylene bags to control anther dehiscence, even an inexperienced person can prepare numerous females in a day.

C. Pollination

Sorghum is self-pollinated simply by placing a paper pollinating bag over the panicle before flowering. Selfs can be made on panicles that have commenced flowering if the flowered portion of the panicle is removed, usually with a knife, before it is covered by a bag. A plant bagged as a pollen source also can be selfed if open-pollinated spikelets are removed and the remainder of the panicle is bagged.

Pollen for crossing should be collected in the morning when anthers dehisce, usually between 0700 and 1200 hours. Any panicle that is flowering can be used as a source of pollen, but pollen is most abundant when taken from the center of the panicle (Fig. 1). Stray pollen on the panicle of the pollen parent usually is not a problem and pollen can be collected from open heads. The male can be covered the day before crossing if one desires absolute protection from pollen contamination or if the wind may agitate the pollen from the anthers of unbagged panicles before all pollinations can be completed. Pollen from bagged heads is shed later and is available for a longer time than is pollen from open heads. To collect pollen, the bag covering the panicle is tilted toward the horizontal and the bag with enclosed panicle is rapped sharply.

On male-sterile and hot-water emasculated panicles, crosses are made after the panicles have completed flowering and the receptive stigmas are extruded, usually in 5 to 8 days after bagging. The bag containing pollen is inverted over the panicle of the female and shaken to promote movement of the pollen onto the stigmas. Alternative methods are to remove the male panicle or a portion of it and brush it on the stigmas of the female or to bag together the panicles of the male and female plants. The panicle of the male plant may be placed in a vial of water attached to the peduncle of the female.

If all of the hand emasculated spikelets on a panicle are intended for the same cross, the previously discussed methods of pollen transfer, or modifications of them are used. Frequently, a single female plant may be crossed by several males or pollen from a single male may be needed for crossing several females. To pollinate under these circumstances, more care is needed in pollen transfer, and an artist's brush is useful for transferring the pollen to the intended stigmas from the bag in which it was collected.

After pollination is completed, the panicles or the individually pollinated panicle branches are covered and the bag is secured with a staple or clip. The identification of the cross (usually a pedigree or plot number) is
written on the bag or a tag attached to the bag or peduncle. Stigmas of flowers properly pollinated will lose their freshness in a few hours.

When *anther dehiscence is controlled*, the polyethylene bag is removed in 1 to 5 days, whenever the desired number of spikelets has opened. The panicle is rapped to remove excess moisture and anthers extruding from the florets (Fig. 7). The panicle is pollinated as described for male-steriles. If it is not desired to pollinate an entire panicle, the unopened spikelets at the base of the panicle should be removed, unless they were removed at the time of female preparation.

The success of pollination varies with personal skill, environment, age of stigmas, abundance of pollen, interference from insects, and amount of injury sustained by the flower parts during emasculation and pollination. Optimally, 80 to 90% of the spikelets will set seed. Pollinations of hand emasculations are consistently good in the greenhouse, but are variable in the field. Also seed set is sometimes low because of heat damage to panicles emasculated by hot water and those covered with polyethylene bags. Excellent success is ordinarily obtained when crossing onto genetic or cytoplasmic-genetic male-steriles.

**D. Factors Affecting Efficiency**

Field nursery arrangements and procedures vary with the types of material to be handled, the tasks to be performed, and the nature of the pollinating crew. Plots are single to multiple rows about 5.5 to 7.6 m long, but may be much longer for certain materials, such as segregating populations. Parallel and adjacent plots constitute a range or tier which is separated from adjacent ranges by alleys. Rows are from 10 to 100 cm apart and plants within rows are from 5 to 30 cm apart, with about 10 cm spacing being common where hand crossing is intended. For some purposes, the plant density within rows should be that used by farmers in production fields. The nursery usually is overplanted and hand-thinned to the desired plant population.

Materials are grouped in blocks within the nursery according to the study and the intended pollinating procedure, e.g., selfing, crossing, population breeding, observations, forage breeding, and tropical conversion. This arrangement permits efficient management of labor because it allows simplified work assignments to be made within clearly identifiable boundaries. A field map of the nursery is useful for orientation. Plot numbers are written on stakes or tags to be placed at the front of each plot, or at least every 10th plot. Different colored tags help identify special materials, such as steriles. Field books contain corresponding plot numbers, pedigrees, and special notes. Notes are recorded in the field book identifying all operations performed on the plot.

Ranges of 100 or fewer plots are most convenient and lines to be crossed are planted near each other, adjacent if possible, to reduce walking distances. Frequently, male-sterile (A) lines are paired with maintainer (B) or restorer (R) lines with which they are to be crossed. Sometimes specific females or males are planted in rows extending along one side of the block,
thus placing them within easy reach from anywhere within the block. It is advisable to put restorer and nonrestorer lines in separate blocks when pollen is to be collected from open-pollinated heads, or in population work in which natural pollination occurs.

Lines to be crossed with several other lines are best planted two or three times at 7 to 10-day intervals to assure that flowering dates are matched. Flowering dates of plants within a plot can be varied by cutting off the panicles of some plants before they flower, thus promoting the formation of tiller panicles to flower at a later date.

At the time of flowering, different-colored pollinating bags can be effectively used to identify panicles handled differently, e.g. plain bags for selfing, red striped for steriles, black striped for crosses. Bagging or pollinating dates are written or stamped on the pollinating bag. Some workers put the cross identification on the pollinating bag, while others prefer to attach to the bag or the peduncle a tag with such information. The nursery is harvested by hand according to a plan prepared by the breeder.

Knowledge of genetic characters permits distinguishing hybrids from selfs in a progeny. Some of the more useful genes as dominant markers are A, B, D, Dw, Ma, P, Pc, R, Rs, Wx, and Y (Schertz and Stephens, 1966). Of the seedling characters, red seedling stems (Rs) is usually reliable. Normal endosperm (Wx) has a unique advantage as a marker when a waxy endosperm (wx) line can be used as the female because the hybrid seed can be identified. Of the dominant mature plant characters, dry midrib (D), plant color (P), seed color (red or yellow, Y, R) and tallness (Dw) are especially useful. Even without the intentional use of a specific dominant genetic marker, it is not too difficult to distinguish hybrids from selfs. If general characteristics rather than specific markers are used, the best times to make observations are at flowering and grain maturity. Sorghum genetic information, including descriptions and linkages are provided in several reviews (Ayyangar, 1942; Quinby and Martin, 1954; Doggett, 1970).

V. NATURAL HYBRIDIZATION

Natural hybridization is used effectively in sorghum. Genetic steriles are used for natural hybridization to promote crossing in random mating populations (Eberhart, 1970). Genes for male sterility, such as ms, (Webster, 1965) are introduced into a population, and hybridization and recombination are continued by selection of male-sterile plants in subsequent segregating generations.

Cytoplasmic-genetic male-steriles can be used effectively to increase hybrid seed for testing. A normal procedure is to plant a fertility-restoring pollinator in an isolation block with several male-sterile females. The wind disperses the pollen under natural conditions and hybrid seed is harvested from each female. This method is an inexpensive and efficient way in which to produce seed for evaluation of a breeder’s selections. Information on the use of natural hybridization for production of commercial seed of hybrid sorghum is provided in Chapter 8.
VI. SEED DEVELOPMENT, HARVEST, AND STORAGE

Seed development can be observed by 7 days after successful pollination and fertilization by removal of opaque bags or viewing through those bags made of transparent material. Physiological maturity, as indicated by the formation of a black layer at the base of the seed, occurs from 35 to 45 days after pollination. Seed is sufficiently mature for hand harvesting at about 30 days after pollination. Successive rains or heavy dews can rapidly deteriorate seed; therefore, under such conditions it is best to harvest seed produced by hand crossing about 30 days after pollination. For harvest, the peduncle is cut below the panicle. One procedure for transporting and drying the panicles is to place a tag identifying the plot or plant on a wire, and to thread either the peduncles or the bags covering the panicles onto the wire. The wire can be hung in a shelter to dry the panicles. Another procedure is to place the harvested panicles in cloth bags and place them in a drying chamber.

Seed will usually be dry enough to thresh in a few days. Seed produced from pollinations of hand-emasculated florets are usually few and may be rubbed out on a corrugated board. Seed from other crosses are usually more numerous, and a small head thrasher is the proper choice. Care must be taken to clean the machine between threshing of seed with different parentages. Seed from an individual cross is placed in an envelope on which the identity is written, and the identifying tag used at the time of crossing is inserted into the envelope.

Sorghum seed may be damaged by grain insects. Seed should be fumigated if it was produced in the warmer climates and is already infested with insects when harvested. Stored seed can be protected by placing naphthalene crystals in the envelopes or in the box containing seed-bearing envelopes. Storage in metal boxes or in sealed jars adequately protects seed from rodents. Environment of storage is also important. A temperature of 10 C and relative humidity of 50% or lower will increase the storage life at most locations and are absolutely essential in areas of high temperature and high humidity. In drier areas, temperature control alone is sometimes reasonably effective. In some of the driest areas, sorghum seed has been stored for many years with neither temperature nor humidity control.

REFERENCES


