Pearl millet, *Pennisetum americanum* (L.) Leeke, is a robust, annual bunchgrass that is grown on more than 20 million ha in the world. It is the world's sixth most important cereal. In Africa and India, it is the principal grain crop in areas too hot and dry for other cereals. In the United States, it makes a high-yielding summer forage of excellent quality.

I. PARENTAL MATERIAL

Pearl millet is an extremely variable species. Plants may consist of a single culm less than 0.5 m in height or many culms 5 m tall. Culms may be simple or branched, slender or stout, smooth or hairy. Leaves and sheaths also may be smooth or hairy. Plant parts may be green, purple, red, or golden yellow.

According to Brunken et al. (1977), “...the greatest morphological diversity in pearl millet occurs today in West Africa south of the Sahara Desert and north of the forest zone. The wild progenitor also occurs in the drier, northern portion of this zone.” Present-day distribution indicates that the sahel zone extending from western Sudan to Senegal is the original home of pearl millet. Other centers of origin that have been proposed include the Ethiopian highlands, Sierra Leone, and the headwaters of the Niger river in the central Sahara (Brunken et al., 1977). The world collection of pearl millet germplasm is small compared to the great variety of landraces in the crop. The International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) in Hyderabad, India, is presently centralizing and enlarging the world collection.
Of the many species in the genus *Pennisetum*, only napiergrass, *P. purpureum* Schumach, is closely related to *P. americanum*. Both species occur in the *Pennisetum* section and have a basic chromosome number of seven. Attempts to hybridize pearl millet with species in other sections that have different basic chromosome numbers have had little success (Burton and Powell, 1968).

Krishnaswamy (1962) reported that *P. americanum* and *P. purpureum* have a common genome, A, and the latter has a second genome, designated B. The triploid interspecific hybrids produce the expected seven bivalents and seven univalents at meiosis.

Many of the sterile triploids are vigorous and have forage potential (Burton, 1944). When such triploids were used as females and backcrossed to each parent, one weak hybrid was found in an estimated 5,000 potential hybrids with each parent. The best of the sterile F₁ hybrids could be propagated vegetatively as a forage crop.

It has been suggested that pearl millet × napiergrass hybrids could be propagated by seed produced by planting cytoplasmic-genetic male-sterile (CMS) pearl millets between rows of napiergrass at a time that would bring both into flower simultaneously (Powell and Burton, 1966). Pearl millet × napiergrass F₁ hybrids established from seed start off slower than pearl millet hybrids, but produce about as much forage in a growing season because they make much more growth in the fall. The future of F₁ pearl millet × napiergrass hybrids depends on the development of a commercially feasible method of seed production. Napiergrass genotypes studied to date have been short-day sensitive and have not started to initiate floral organs until the photoperiod was less than 12 hours. As a consequence, it has been impossible to produce seed of CMS pearl millet × napiergrass before frost in most of the continental U.S.

Several workers have developed amphidiploids of pearl millet × napiergrass hybrids. Although somewhat fertile, these amphidiploids have been unstable and nothing of economic importance has resulted from the considerable effort expended (Burton and Powell, 1968).

**II. PLANT CULTURE**

**A. Field**

Most pearl millet genotypes stool a great deal when given adequate space. At Tifton, Ga., nurseries are planted with cone planters and measured volumes of seed that place 10 to 15 seeds per 1 m of row. Plants are thinned to one plant for every 0.3 to 0.4 m. Rows are alternately spaced 0.6 and 1.2 m apart to give more room to bag heads and make hybrids. Growth of the millet in this 0.6, 1.2, 0.6, 1.2 m spacing is similar to that in rows uniformly spaced 0.9 m apart. Propazine [2-chloro-4,6-bis(isopropylamino)-s-triazine], applied at a rate of 2 kg/ha on loamy sand soils immediately after planting, effectively controls weeds without apparent injury to pearl millet.

Photoperiods that bring pearl millets into flower permit hybridization and seed set. Photoperiods of less than 12 hours tend to bring all genotypes
into flower at the same time and thus facilitate the hybridization of genotypes that differ in photoperiodic response.

The temperature extremes that limit flowering and seed set in pearl millet have not been established. It has been known to flower and set seed at temperatures between 25 and 45°C.

Pearl millet flowers in a relative humidity of 100%, such as that obtained when heads are enclosed in plastic bags, but it does not set seed in such bags. Under natural conditions, the relative humidity never seems to get too low for hybridization and seed production.

Pearl millet can grow, flower, and produce seed on soils that range from infertile sands to highly fertile loams. Because most pearl millets reach heights of 2 to 4 m on fertile, well-watered soils, plants can be more easily hybridized if the soil fertility is kept low.

Pearl millet tolerates little flooding, but can be hybridized and made to set seed under considerable moisture stress.

### B. Growth Chamber and Greenhouse

Maintaining temperatures above 25°C seems to be the only special requirement for growing and hybridizing pearl millet in greenhouses, nurseries, and growth chambers during the winter months.

Supplemental light has not been required for normal flowering and seed set in pearl millet during winter months at Tifton, Ga. Pearl millet has flowered and set seed in growth chambers with only 8 hours of light per day at 43 to 48 klux, attained from 70% input wattage of cool-white fluorescent lighting and 30% input wattage from incandescent lighting (Helmars and Burton, 1972).

### III. FLORAL CHARACTERISTICS

The inflorescence (head) of pearl millet is a false spike ranging from 5 to more than 150 cm in length and from 1 to 5 cm in diam. The involucre, borne on a stalk up to 15 cm long, consists of a cluster of bristles that are usually inconspicuous in mature heads, but may extend several cm beyond the grain. The spikelets, 4 to 7 mm long in each involucre, usually occur in pairs with a sessile male floret and a short pedicelled bisexual floret. The latter has a single pistil with two feathery styril branches and three anthers enclosed between the lemma and palea. The styril branches are usually colorless, but in one genotype they develop a red color when exposed to the sun.

Pearl millet is a protogynous species, and the styril branches are extended from the florets several days before the anthers. The protogynous flowering habit facilitates cross pollination. Natural crossing is not complete because plants have several culms that flower in succession. This allows the head that reaches anthesis first to pollinate other heads on the same plant that are just exserting anthers. As a consequence, self-pollination as high as 31% has been observed (Burton, 1974).
Stylar branches are first exerted from florets in the upper half of the head, and by the third day nearly all styles emerge on heads less than 25 cm long. Longer heads usually require more days for complete exertion of all stylar branches. Styles are usually exerted after the heads emerge from the boot, but in some genotypes they are exerted before head emergence. Seed set is usually very poor if anthesis occurs in the boot.

The first anthers generally emerge from the first florets to exert styles at least 1 day after most styles on a head are exerted. Anthers in the sessile male florets are exerted 2 or 3 days later. Most heads shed pollen for 4 to 6 days. When temperatures exceed 25 C, anthesis occurs anytime during the day with the greatest flush of anthers appearing soon after sunrise. On cool fall nights, anthesis is delayed until one or more hours after sunrise and occurs first on the east side of the heads.

Stigmas in a floret remain receptive from emergence until 1 day after its anthers have been exerted. Heads of cytoplasmic male-sterile ‘Tift 23A’, pollinated 2 to 3 days before anthesis, set more seed than those pollinated after anthesis begins (Burton, 1966). Many florets that set seeds on heads pollinated 3 days before anthesis had not exerted stigmas when the head was pollinated. Thus, pollen either entered the opening at the apex of the floret to effect fertilization immediately or remained viable at the stylar opening of the glumes until the styles were exerted.

Pearl millet pollen collected in glassine bags and stored in sealed glass jars at 27 C for 1, 2, 3, and 4 days before application to receptive heads of cytoplasmic male sterile Tift 23A was 59, 10, 3, and 1% as effective as fresh pollen, respectively (Cooper and Burton, 1965). When stored at 4 C for 1, 2, 3, and 4 days, it was 96, 95, 82, and 71% as effective as fresh pollen, respectively. When stored at 4 C for 21 days and then applied to Tift 23A, it was still 8% as effective as fresh pollen.

Fertilization occurs within a few hours after pollination. Stylar branches wilt and usually are dry 24 hours after pollination.

IV. ARTIFICIAL HYBRIDIZATION AND SELF-POLLINATION

A. Equipment

The equipment for hybridization and self-pollination includes bags 7.5 x 35 cm in size made of 11.35 kg (26 lb) bleached waterproof glassine sealed with waterproof glue, similar bags made of 22.70 kg (50 lb) kraft paper, a stapling plier or standard paper clips to fasten the bags on the heads, and a coarse pen with waterproof ink.

If grain-destroying insects, such as the sorghum webworm, Celama sorghiella, Riley, and the corn earworm, Heliothis zea Boddie, are present, they must be controlled by spraying the millet with a suitable insecticide before bagging or by treating the bags with an insecticide. An insecticide such as aldrin (1, 2, 3, 4, 10, 10-hexachloro-1,4,4a,5,6,9B-hexahydro-1,4-endo-exo-5,8,-dimethanonaphthalene) mixed with mineral spirits (1 liter to 0.908 kg/3.784 liter (2 lb/gal) aldrin emulsion per 40 liters of mineral spirits) can be impregnated in the kraft bags by dipping bundles of the bags in a wash
tub of the chemical mix, draining off the excess, and drying them in the greenhouse.

B. Preparation of the Female

To prepare the female parent, the top one or two leaf blades are removed and the partially exserted head and culm are covered with a glassine bag before styles appear (Fig. 1 and 2). The bag is fastened by folding the open end at a 45° angle and stapling it close enough to the stem so that it does not blow off. It must be loose enough, however, to be moved up the culm by the exserting head.

The protogynous habit of pearl millet makes emasculation unnecessary. Instead of emasculation, the hybridizer examines the head by looking through the glassine bag for the presence of exserted styles. When styles are exserted, the head is ready to pollinate (Fig. 3). Some genotypes start ex-
serting anthers before the florets at the top and the bottom of the head are exserted. On such genotypes, the florets without stigmas can be removed at the time of pollination without adversely affecting the pollination and seed set of those remaining on the head.

C. Pollination

Selfing in pearl millet is easily accomplished by removing the top one or two leaf blades of the culm and enclosing the head and culm in a kraft bag before any styles appear (Fig. 4). The bag is stapled together as described for the glassine bags. The bag is left on the head until it has been harvested, dried, and prepared for threshing.

Crosses are made by using as females, heads that have exserted their styles but not their anthers (Fig. 3). Pollen can be collected any time that it is dry. Glassine pollen-collecting bags allow the worker to see the amount of pollen available. Shaking the pollen-collecting bag vigorously and carefully

![Image](image_url)

Fig. 2—Head enclosed in 7½ × 35 cm glassine bag.
removing it from the head maximizes the amount of pollen harvested. Although crossing can be accomplished at any time, the seed set from crosses made at midday is lower than that from crosses made earlier and later in the day (Cooper and Burton, 1965).

Pollen is usually applied by putting the female head in the bag in which the pollen was collected and shaking it. If the female millet is tall, the culms are bent over so that the head assumes a nearly horizontal position before the pollen-containing bag is pulled over it. If the female is 1 to 2 m tall, the opened pollen-containing bag can be rapidly inverted and pushed down over the head before pollen can fall from it. It is possible to pollinate two female heads at the same time in a good bag of pollen.

After pollination, the head or pair of heads are enclosed in a kraft bag on which is written the pedigree of the cross, the date, and any other pertinent information (Fig. 4). These bags are left on the heads until they are threshed. Insecticide-treated bags protect the seed from insects, and bags usually protect the seed from birds. If pollen is fresh and abundant, nearly 100% seed set can be expected.
D. Factors Affecting Efficiency

Nurseries are arranged to minimize walking by grouping together lines to be hybridized, lines with similar maturities, and lines that otherwise form logical units.

Hybridization of lines with different flowering dates is accomplished by planting lines to be hybridized at 10-day intervals to cover the expected range in maturities. Most millet lines develop branches from the upper nodes that bear flowering heads 3 to 5 weeks after the primary head flowers. These secondary heads can often be used to make hybrids missed on primary heads.

Photoperiod, temperature, and drought alter flowering dates in pearl millet. Some genotypes fail to flower when day lengths exceed 12 hours (Burton, 1965). Other genotypes flower in long days (16-hour photoperiod), but flowering is earlier under short days (Begg and Burton, 1971; Burton,

Fig. 4—Head enclosed in 7½ × 35 cm kraft bag after pollination.
When planted in the winter in Puerto Rico or in the greenhouse at Tifton, Ga., with temperatures above 30 C, both "day neutral" and short-day millets flowered at about the same time (Barnes and Burton, 1966). An automatic darkbox can be used in summer to subject 3-week-old potted plants of pearl millet to 10 hours of light for 4 weeks and induce near simultaneous flowering in genotypes with different day-length requirements (Burton and Stansell, 1971).

Increasing the growing temperatures up to 32 C and providing the appropriate photoperiod reduces the number of days from planting to flowering (Hellmars and Burton, 1972).

Observations suggest that drought may hasten flowering in some genotypes, like 'Tift 186', and may delay flowering in other genotypes, such as 'Tift 23DB' and 'Tift 239'.

Pearl millet hybrids are much more vigorous than inbred lines and can be easily identified on this basis if the parents are inbreds. The hybrid nature of offspring can be determined with a number of simply inherited plant characters in pearl millet such as dwarfness, trichomelessness, and plant colors.

V. NATURAL HYBRIDIZATION

Before CMS was discovered, 'Gahi 1' pearl millet gave growers of forage most of the increased production that results from hybrid vigor (Burton, 1958a). Gahi 1 seed is produced commercially by harvesting all seed from isolated fields planted to a mixture of equal numbers of pure live seeds of the four inbreds 13, 18, 23, and 26. These inbreds, selected from many that were tested in diallels, gave high-yielding hybrids in all combinations. Because Gahi 1's parental inbreds flower at the same time, complete inbreeding occurs and about 75% of the seed produced is a mixture of the six possible crosses among the four inbred parents. The other 25% of the seed consists of selfs and sibs of the four parents. When planted at recommended seeding rates, the Gahi 1 seed mixture yields as well as the double cross between the four lines because the more vigorous F₁ hybrid seedlings crowd out and eliminate the inbred seedlings (Burton, 1948).

Inbreds 13, 18, 23, and 26 are increased in isolation and are mixed together in equal numbers of pure live seeds by the National Foundation Seed project to produce foundation seed of Gahi 1. Seed producers must plant only Gahi 1 foundation seed to produce commercial Gahi 1 seed. Only seed harvested from fields planted to Gahi 1 foundation seed can bear the name Gahi 1.

CMS was first discovered in pearl millet in 1956 and was incorporated into inbred Tift 23, an excellent maintainer (Burton, 1958b; Burton, 1965). Two other cytoplasm sources (A₁ and A₂) were later discovered, and 'Tift 239' became an excellent maintainer for the A₁ source (Burton and Athwal, 1967, 1969). Introducing the d₁ gene that cuts plant height in half by a backcrossing program produced 'Tift 23DA', which differed from Tift 23A only by this recessive dwarfing gene (Burton, 1969a; Burton and Fortson, 1963). Tift 239 is also dwarfed by the d₂ gene. Maintainer lines carry the letter B in
their name. Thus 'Tift 23B' is the maintainer for Tift 23A. Lines that carry the dominant fertility restorer gene, *Ms*, are called R lines (Burton and Athwal, 1967).

The first commercial F₁ grain-producing hybrid was released in India in 1965. Named 'HBI', this hybrid had outyielded many other experimental hybrids and had produced 88% more grain than the best open-pollinated check in numerous yield trials throughout India's millet belt (from 11 to 31°N Lat) prior to its release. HBI is a cross between Tift 23A and the restorer R line Bil 3B (Burton and Powell, 1968). Indian farmers planted HBI as rapidly as seed could be produced and increased pearl millet grain production in India from 3.5 million metric tons in 1965 to 8.0 million metric tons in 1970. A number of other grain-producing hybrids have been released and are currently being grown in India.

In the United States, several F₁ hybrids have been released for forage production. Most of these have Tift 23A or Tift 23DA as the female parent. Forage hybrids remain vegetative longer and do not become weeds for succeeding crops if they produce no seed. Using sterility maintaining B lines as male parents will achieve this end.

The *d₁* gene that reduces plant height 50% and facilitates seed production also increases leafiness, forage quality, and animal performance. Tifeaf ₁ is the first commercial forage hybrid dwarfed with the *d₁* gene (Burton et al., 1969; Johnson et al., 1976).

Commercial F₁ hybrid seed is produced by planting 6- to 12-row strips of the CMS female parent between 2-row strips of the male parent. Only the CMS rows are harvested and sold as hybrid seed.

Seed-certifying agencies set minimum isolation requirements for certified seed. Pearl millet pollen, although largely wind-borne, can be carried up to 1.6 km by bees (*Apis mellifera* L.) (Leuck and Burton, 1966). Isolations for breeders seed should be 1.6 km or more, and fields planted to breeders seed should be checked for rogues. In the tropics and subtropics, the growing season is long enough to mature two or more crops per year in the same field. Time, in the form of staggered plantings, can provide isolation. Both A, and A, CMS cytoplasms mutate to normal pollen-shedding cytoplasm (Burton, 1977b). These pollen-shedding plants seem stable and act as maintainers. Although the frequency of pollen shedding mutants is low, pollen from them can fertilize florets on CMS plants in seed fields. Seeds fertilized by the pollen shedders give rise to weak CMS plants that may reduce forage yield of the hybrid. In India and Africa where ergot infects pearl millet florets and poisons the grain, CMS plants are more apt to develop ergots than fertile pollen-shedding hybrids. Pollen-shedding mutants should be rogued from CMS seed increase fields and limited generation increase should be practiced to reduce the frequency in hybrid seed production fields.

Pearl millet hybrids outyield cultivars under favorable conditions and show even greater superiority when grown under the stresses to which pearl millet is exposed. For these reasons, hybrids would be used in the developing countries if hybrid seed were easily obtained. Research at Tifton, Ga., suggests the following procedure to solve the problem of seed supply. A central government agency can increase the parents and produce a hybrid
foundation mix containing 85 to 90% of the CMS parent and 10 to 15% of the fertility-restoring male parent. This foundation mix can be distributed to selected farmers for increase in isolation. These farmers can harvest all the seed produced (the small amount of male inbred seed harvested would be crowded out by the hybrids, as in Gahi 1) and exchange it with their neighbors for two or three times as much grain. The neighbors planting the hybrid seed can harvest enough additional grain (more than that from their old cultivars) to much more than cover the grain cost of hybrid seed.

VI. SEED DEVELOPMENT, HARVEST, AND STORAGE

Seed set can be checked visually by examining the heads about 10 days after pollination.

Pearl millet should be harvested as soon as the grain is mature. The peduncles remain green for several weeks after the grain is mature; thus the heads must be dried before they can be threshed. At Tifton, Ga., bulk lots of heads are dried on plastic sheets on the floor of empty greenhouses. A concrete floored greenhouse sprayed with a dilute white latex paint to reduce light and heat penetration is used to dry and store bundles of selfs and hybrids after harvest. After they have been dried in the greenhouse, single heads are threshed in small nursery threshers. Either tooth or bar cylinder threshers work well with pearl millet if the heads are dry. Nursery threshers work best if the heads are preconditioned for several hours in a forced-air electric oven set at 40 C.

Pearl millet seeds are difficult to differentiate other than by number and pedigree.

At Tifton, Ga., pearl millet seeds dried to less than 12% moisture and stored in airtight containers at 5 C have germinated well (70%) after 26 years (Burton, 1976). I believe that good quality millet seeds, dried to 5 to 7% moisture content in a forced-air oven at 40 C, sealed in airtight containers, and stored at −20 C, will retain their viability for at least 100 years.

VII. TECHNIQUES FOR SPECIAL SITUATIONS

Seeds of most pearl millet genotypes are dormant for several weeks after they mature. Seed dormancy usually breaks down in a few weeks at warm temperatures, but it may last for more than a year if the seeds are stored at 4 C soon after they mature. To grow several generations a year, dormancy must be broken as soon as seeds mature. Soaking seeds for 1 hour at 20 to 25 C in a water solution of 1% 2-chloroethanol plus 0.5% sodium hypochlorite has increased the germination of dormant pearl millet seeds more than a number of other treatments tested (Burton, 1969b).

Birds are fond of pearl millet seed and can quickly consume all the grain in small seed fields or yield plots. At Tifton, Ga., spraying the heads with the cotton insecticide, monocrotophos [dimethyl phosphate ester with (E)-3-hydroxy-N-methylcrotonamide], has controlled grain-destroying insects and has also served as an excellent repellent for sparrows and blackbirds. Rates of 375 g/ha (0.75 lb/A) of actual monocrotophos have given good results. Repeated applications have sometimes been necessary.
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