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Training Manual

Development of Cultivars and Seed Production Techniques in Sorghum and Pearl Millet

International Crops Research Institute for the Semi-Arid Tropics

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Development of Cultivars and Seed Production Techniques in Sorghum and Pearl Millet

Edited by

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ICRISAT

Training and Fellowships Program and Genetic Enhancement Division

International Crops Research Institute tor the Semi-Arid Tropics

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About this manual

Sorghum and pearl millet are important coarse-grain cereals in the dry agricultural areas of the arid and semi-arid tropics. In both crops, varieties (open-pollinated and highly heterogenous/heterozygous types in pearl millet and homozygous/homogenous types in sorghum) and hybrids (based on cytoplasmic-genic male sterility) have been produced and adopted by farmers. The development of parental materials and their use in cultivar development and seed production of new varieties requires specific skills. With the aim of imparting such skills, a training course was organized for scientists and technicians from Asia and Africa at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), India, from 6 to 17 Mar 1995.

The course covered both theoretical and practical aspects of development and maintenance of cultivars (hybrids and varieties) and their parental lines. The participants were given overviews of cultivar development of both crops. The course broadly covered topics such as the reproductive biology of both the crops, selfing and crossing techniques, production and maintenance of male-sterile lines, restorer parents and hybrids, and varieties in sorghum and pearl millet. Production of foundation and certified seeds, postharvest handling of breeder seeds, and seed testing procedures were also discussed. A chronology of events relating to the development of the seed industry in India was also included in the course. The participants were taken to seed processing plants near Hyderabad, India.

There were eight participants (Annexure I) from Egypt, Kenya, Mali, Myanmar, Namibia, Niger, Nigeria, and Syria. The resource persons for the course were from ICRISAT Asia Center, and public and private sector seed-producing organisations in Hyderabad, India. This manual is a compilation of lectures delivered by the resource persons. Although some editing has minimized a great deal of duplication across the chapters, some duplication of content has been purposely retained to avoid any discontinuity within the chapter.

It is hoped that this manual will be of use to scientists and technicians involved in the development of sorghum and pearl millet cultivars and their seed production.

Information has been taken from published and unpublished reports. Efforts have been made to indicate trade names® where available. Omission or inclusion of any trade name does not constitute endorsement or discrimination of product by ICRISAT or the contributors to this publication.

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Contents

Sorghum

An Overview of Sorghum Cultivar Development

J W Stenhouse

Sorghum (*Sorghum bicolor* (L.) Moench) is the fifth most important cereal crop in the world after wheat, rice, maize, and barley. It is cultivated annually over approximately 45 million ha, producing approximately 60 million t of grain. Sorghum grain is a major food in much of Africa, South Asia, and Central America, and an important animal feed in the USA, Australia, and South America. In addition to these uses of the grain, sorghum crop residues and green plants also provide sources of animal feed, building materials, and fuel, particularly in the semi-arid tropics (SAT).

Sorghum is adapted to tropical and subtropical climates but the greater part of the area of the crop falls in drought-prone, semi-arid tropical regions of the world. In these areas, it is usually grown with limited inputs in conditions of sparse rainfall and low soil fertility, and exposed to a range of diseases and pests. As a result, the yields are poor.

In fact, the yield potential of sorghum is quite high; grain yields can exceed 10 t ha^{-1} under favorable conditions. However, a majority of the subsistence farmers who typically cultivate this crop are unable to take advantage of this potential because they have limited options for improving their management practices. Hence, improvements in sorghum production in the SAT are more readily achieved through seed-based technologies such as cultivars with improved tolerance to drought and low soil fertility, and resistance to pests and diseases.

Breeding Behavior of Sorghum and Types of Cultivars

The breeding behavior of a crop influences the methods used by plant breeders to produce improved cultivars and the types of cultivars that can be developed.

Sorghum is a predominantly self-pollinating crop which shows little inbreeding depression. However, significant levels of natural outcrossing also occur. The level of outcrossing varies according to the panicle type of the cultivar. It can be as much as 30-60% in loose-panicled grassy sorghum, but a more typical figure would be <10% in compact-panicled types (House 1985). As a result of this combination of self-pollination and outcrossing, most of the landraces of sorghum that are normally grown by subsistence farmers *are* mixtures of inbred and partially inbred lines. Improvement can be achieved by purification of the more productive lines in the mixture by selfing to develop pure-line varieties. However, because of the tendency for further outcrossing to occur, these pure-line varieties require deliberate maintenance by selfing to keep them pure.

Several male sterility systems are found in sorghum which can be used by plant breeders to widen the range of possibilities for improving the crop and to develop different cultivar types. Genetic male sterility, which is controlled by recessive genes at any one of several loci (Doggett 1988), can be used to promote outcrossing and generate random-mating populations for improvement by various recurrent selection methods. In particular, male sterility caused by ms_3, ms_7, and a/genes has been used for this purpose (Murty et al. 1994). These random-mating populations of sorghum, unlike other crops, are rarely suitable for direct use by the farmer because of their ragged appearance (House 1985).

Several cytoplasmic genetic male sterility (CMS) systems occur in sorghum (Schertz and Pring 1982). These can be used to capture heterosis in hybrid cultivars by crossing two inbred lines, one male-sterile and the other male-fertile. The Milo-Kafir CMS system discovered by Stephen and Holland (1954), also known as the A, CMS system, is the most commonly used system for commercial production of hybrids. Like the pure-line varieties mentioned above, the inbred line parents of hybrids require deliberate and systematic maintenance to keep them pure, particularly the CMS parent. The seed of the hybrid cultivars themselves must also be regenerated afresh each time it is required because the hybrids do not breed true following self-pollination.

Breeding Objectives

Sorghum is grown in a wide range of physical conditions in locations ranging from the equator to over 50°N and 30°S. The crop is therefore subject to a wide variety of temperature, day-length, and moisture regimes. Thus breeding improved sorghum cultivars for a particular environment always involves breeding for adaptation to the specific climatic conditions found there. This is usually indicated by the appropriate crop duration for that environment and by acceptable and stable yield levels and appropriate grain qualities.

The type of cultivar required for a target location also influences the objectives of the plant breeder. For example, the height of a pure-line variety for a specific environment and the heights of the parental lines of a hybrid for the same environment are likely to be different.

In addition, improved cultivars for specific locations must possess resistances to the major constraints to production encountered and grain- and stover-quality factors appropriate for sorghum there. These constraints include biotic — such as diseases, insects, and parasitic weeds — and abiotic stresses, the requirements for which are usually quite different from one location to another. Resistances to these constraints are deliberately bred into cultivars by crossing resistant types with cultivars possessing other desirable traits and selecting plants with both resistance and desirable traits. Some of the constraints for which resistances are commonly required or which otherwise influence the type of cultivar required are outlined below.

Biotic Constraints

Diseases

Charcoal rot. A common fungal disease of the drier sorghum growing areas, particularly those with terminal drought stress, charcoal rot (*Macrophomina phaseolina)* is characterized by lodging and presence of black *sclerotia* on the vascular tissues of the lower stem. It causes reduced grain size and loss of grain due to lodging.

Anthracnose. The most important fungal leaf disease in West Africa, anthracnose (*Colletotrichum graminicola*) can also attack the stalk and panicle, causing severe loss of grain and affecting the quantity and quality of stover.

Leaf blight. Leaf blight (*Exserohilum turcicum*) is common in the cooler sorghum producing environments such as southern Africa. An attack by this fungal pathogen predisposes plants to stalk rots.

Grain molds. Caused by a complex of pathogens (*Curvulaha, Fusarium, Phoma* spp) which attack the developing and maturing grain in hot and humid conditions. Grain molds can cause severe loss of

quantity and quality of grain. Severely infected grain appear discolored to the naked eye. Grain molds are often accompanied by sprouting of the seed while still on the plant with severe consequences for viability and seed quality.

Sorghum downy mildew. Characterized by chlorotic, stunted plants with white downy growth on the abaxial surface of infected leaves. Sorghum downy mildew *(Peronosclerospora sorghi*) may cause the death of the plant when infection occurs early. In later stages, leaves turn yellow and often show shredding at the tip. Diseased plants are often barren or partially so.

Other diseases. Sorghum is subject to a large number of other fungal, bacterial, and viral diseases, most of which are of local or sporadic significance. These include: seedling rots (*Pythium, Fusarium, Aspergillus, Rhizoctonia, Phoma* spp), foliar diseases (gray leaf spot, zonate leaf spot, rough leaf spot, oval leaf spot, sooty stripe, rust, and crazy-top), and panicle and seed diseases (head smut, loose kernel smut, covered smut, long smut, head blight, and ergot). Several of these diseases are of significance for seed multiplication as they can be seedborne.

Insects

Shoot fly. Found only in Asia and Africa. Shoot fly *(Atherigona soccata)* attacks the seedling before the sixth leaf stage and causes drying of the central leaf and deadhead symptoms, particularly in late sowings. Smaller plants may be killed but larger ones usually survive by producing tillers. Tillers often flower later than the main stem, resulting in crop losses.

Stem borers. Four species of stem borers are of significance in sorghum in various parts of the world: the spotted stem borer *(Chilo partellus),* maize stalk borer *(Busseola fusca),* African pink borer *(Sesamia calamistis),* and African sugarcane borer *(Eldana saccharina)* are the main concerns. They attack the crop at any stage, causing deadheart symptoms in young plants, shot holes in the leaves, and tunneling of the stem and peduncle. Late attack can cause breaking of the peduncle and reduced grain filling.

Sorghum midge. Larvae of sorghum midge *(Calocoris sorghicola)* feed on developing grain and cause empty/chaffy spikelets. Grain yield is directly affected as infested spikelets invariably set no seed.

Head bugs. Two main species, *Calocoris angustatus* in India and *Eurystylus immaculatus* in West Africa, suck the developing grains. This causes direct losses and also predisposes punctured grain to mold attack. Grain attacked early fail to develop, while older grain are reduced in size, thus affecting grain yield and quality.

Other insects. A number of other insects attack sorghum at various stages of growth and can cause losses. Most are sporadic in occurrence and of limited general importance. They include: seedling pests (wireworms and white grubs), foliage feeders (spittle bugs, aphids, shootbug, armyworms, grasshoppers, and spider mites), and storage pests. As with diseases, several of these insects are of significance for seed production as they can cause reduced seed size or quality resulting in impaired viability.

Parasitic Weeds

Striga. Several species of *Striga* (*S. hermonthica, S. asiatica,* and S. *forbesii*) attack sorghum plants by sticking to the root and drawing water and nutrients from the host plant, particularly under dry and low-fertility conditions. Striga attack can severely stunt the sorghum plant and cause drying and failure to produce seed heads.

Abiotic Constraints

The main abiotic constraint to sorghum production is drought. This follows from the nature of the environments in which sorghum is commonly grown, where rainfall is often low and erratic. The crop has natural adaptation to dry environments but there is variability among cultivars for drought tolerance, which can be captured for particularly dry conditions.

Sorghum is also grown in environments far from the equator where temperatures, particularly at the beginning of the growing season, are often low. Specially selected sorghum with adaptation to germination in low temperatures are required for such areas. Similarly, where sorghum is grown at high altitude, such as in eastern Africa and Mexico, adaptation to low temperature throughout the growing period is required.

Other abiotic stresses for which tolerance is often required in sorghum include high and low temperatures at flowering, both of which can cause sterility problems; soil factors such as low fertility and acidity; high temperatures, drought, and soil crusting during germination; and terminal drought stress.

Quality Considerations

Sorghum grain and stover are put to many different uses in different parts of the world. These uses influence the types of cultivars grown by farmers. Food uses vary tremendously from location to location, and require different grain textures and colors. For example, sorghum *injera* eaters in Ethiopia prefer a soft white grain as it gives the preferred texture and color to the *injera.* Sorghum beer drinkers in eastern Africa prefer high-tannin brown-grain sorghum which gives their beer the bitter flavor they like. Sorghum eaters in West Africa prefer a hard-grain sorghum which gives their porridge the right consistency. Similarly, forage sorghum for northern India must combine high yields of green matter with the appropriate quality of forage for animal consumption.

Seed Production and Maintenance of Improved Cultivars

Developing improved cultivars of sorghum requires considerable expenditure of time and effort to put together the specific combinations of traits needed to achieve high and stable production of grain and/or stover in a particular environment. These traits include the correct phenology for the environment, the necessary resistances to the biotic and abiotic constraints prevalent there, and the quality traits preferred by farmers.

If improved cultivars are not maintained systematically, they are likely to deteriorate in yield and quality due to outcrossing with the unadapted cultivars lacking one or more of the component traits. Deliberate and systematic maintenance of cultivars and multiplication of their seed is, therefore, required to ensure that the genetic package assembled by the plant breeder is kept together and delivered to farmers. Similarly, attention should be given to the crop health of seed-production plots to ensure that the seed delivered to farmers is in good condition to germinate and establish the intended crop.

Reproductive Biology of Sorghum

Faujdar Singh

Sorghum *(Sorghum bicolor* (L.) Moench.) is a major food and feed crop, grown extensively in the marginal rainfall areas of the tropics and semi-arid regions of the world. The origin of cultivated sorghum has been traced to Africa, particularly Ethiopia, Sudan, and the East African region (Doggett 1965). Cultivated sorghum evolved from the wild *Sorghum bicolor* subsp *arundinaceum.*

Germination and Seedling Development

At optimum temperature (25-30°C) and moisture, the sorghum seed germinates in 3-5 days. The seed absorbs water and swells, thereby breaking the seed coat. A small coleoptile and radicle (primary root) emerge (House 1985). The coleoptile (Fig. 1) begins to emerge from the ground and the first leaf breaks through the tip. As the young plant begins to grow, it bears more leaves. The mesocotyl grows during this period and a node is formed at the base of the coleoptile, just below ground level. The young seedling takes its nutrients from the endosperm. Secondary roots develop in 3-7 days. Gradually, the mesocotyl dies and the seedling's nutritional requirements are met through the new roots. Sorghum remains in vegetative phase for 30-40 days.

Root System

The sorghum root system consists of three types of roots (Fig. 2).

Primary roots. These roots develop from the radicle and die subsequently, leaving a rudiment of them in the plant.

Secondary or adventitious roots. These develop from the first internode on the mesocotyl. They occupy a 5-15 cm area in the soil around the base of the stem. Adventitious roots are small, uniform, and form only a small portion of the root system.

Another type of permanent adventitious roots develops from the second internode and above. These roots are branched laterally (about 1 m^2), interlacing the soil vertically. They mainly supply nutrients to the plant.

Brace (buttress) roots. These roots (Fig. 2) develop from the root primordia of the basal nodes above ground level. They are stunted and thick above ground level, but in the soil they are thin. Brace roots provide anchorage to the plant.

Shoot System

The shoot system includes the stem, leaves, and nodes and internodes during the vegetative stage (Fig. 2).

Stem. The stem or culm of sorghum consists of many alternating nodes and internodes. It ranges from slender to very strong, 0.5-5 cm in diameter near the base, and 0.5-4 m in length (House 1985).

Each node appears as a ring at the base of the leaf sheath. This is the point at which the leaf is attached to the stem. A bud is formed at each node except the one bearing the flag leaf. At times, these buds develop tillers.

Peduncle. The topmost internode bearing the panicle is the peduncle. The larger the diameter of the peduncle, the larger is the panicle size. The peduncle may be straight or curved.

Bloom. The waxy coating on the surface of the internodes is bloom. It prevents transpiration.

Tillers. Tillers develop from the axillary buds situated at the nodes. Basal tillers develop from the axillary buds of the lower nodes, and nodal tillers from the axillary buds of the upper nodes.

Leaves. The leaves are borne alternately in two ranks (Fig. 2) along the stem. A leaf consists of a sheath and a blade or lamina. The sheath is attached to the node and surrounds the internode, and frequently, the node above it. The outer surface of the sheath is covered with bloom. The blades are broad at the base and taper upward to a fine point. They are glabrous, except on the inside just above the ligule and on the outside near the junction with the sheath. Leaf-blade margins are smooth or scarbid. The midrib is prominent, greenish, brown or white. The blades are thicker at the base than at the tip and along the midrib than along the margins. There is a short (1-3 mm), triangular, membranous ligule at the junction of the leaf blade and the sheath. The ligule deflects the lamina from the stem at an angle.

In cultivated sorghum the number of leaves is usually 14-17. The leaves in the middle of the plant are slightly longer than those in the upper part. The topmost leaf, which is short and broad, is called boot leaf or flag leaf. The leaves may be as long as 1 m and may vary in width from 10 to 15 cm (House 1985).

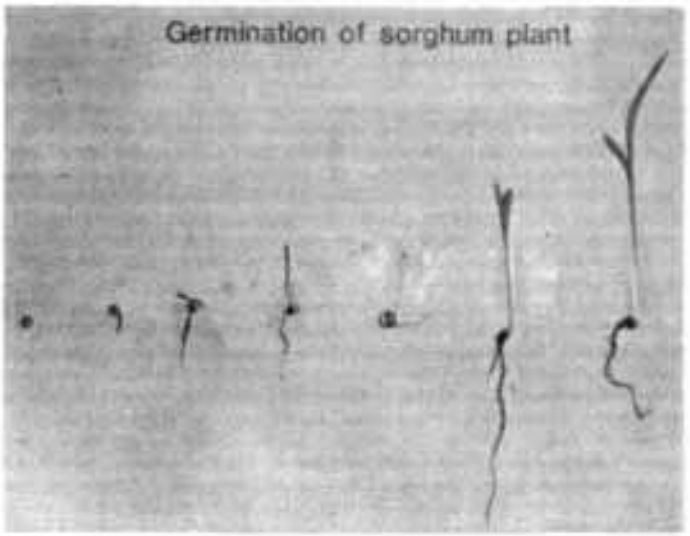
The white ear-shaped structures on both sides of the base of the lamina are the auricles. They act as hinges to facilitate the movement of the lamina.

Reproductive System

Inflorescence. The inflorescence of sorghum is a panicle. The vegetative primordium (growing tip) differentiates into the reproductive primordium (Fig. 3). The shoot apex elongates into the main axis of the inflorescence, which is called the rachis. The rachis tapers off towards the top and is grooved longitudinally. It possesses three types of hairs: (a) the fine types spread in the rachel furrows; (b) the long hairs on the rachel ridges; and (c) the scarbid hairs on the ridges. The rachis elongates and forms branches and branchlets with a rapid increase in dimensions. This results in the formation of primary-, secondary-, and tertiary-branch primordia. The tips of the tertiary-branch primordia develop into two paired spikelet primordia, one hermaphrodite and the other staminate. In some cases, one hermaphrodite and two staminate spikelets are seen. The development of spikelets and florets in the inflorescence continues covered by the flag leaf. The primordial differentiation into floral parts may take about 30 days after sowing (House 1985).

Sorghum panicles vary morphologically, ranging from compact to open. After the complete unfolding of the flag leaf, the peduncle elongation forces the panicle out of the leaf sheath (boot). The part of the peduncle between the base of the lamina of the flag leaf and the base of the peduncle is exertion.

Figure 1. Sorghum germination.



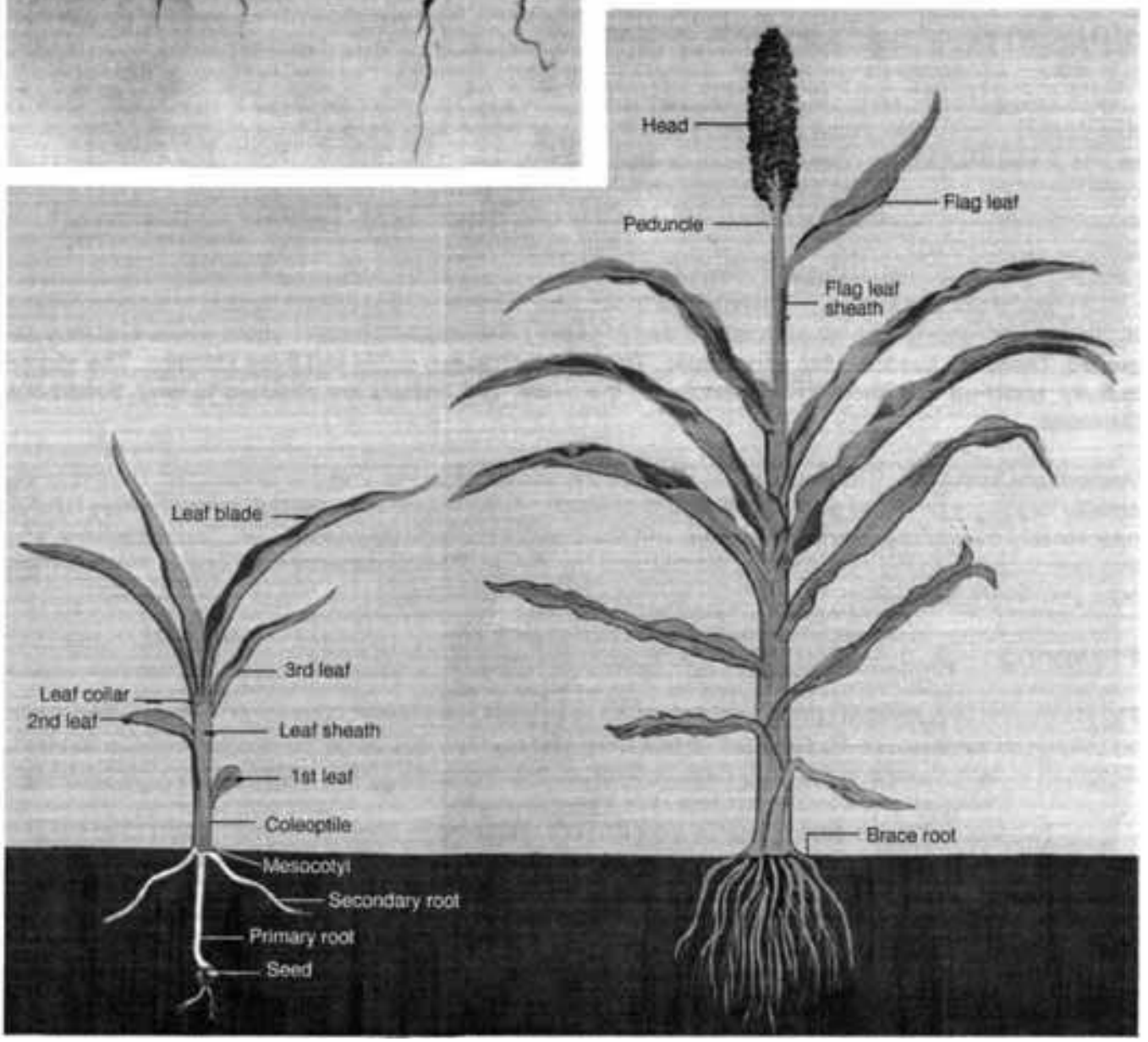


Figure 2. Stylised sorghum plant and parts.
(Source: Vanderlip 1979)

The variation in shape, size, and length of sorghum panicles is due to variation in rachis length, branch length, distance between whorls, and the angle of branching. Sorghum spikelet development is basipetal: those in the upper region of the panicle develop earlier than those in the lower.

Raceme. A raceme consists of one or several spikelets. One spikelet of a raceme is always sessile and the other pedicellate, except the terminal sessile spikelet, which is accompanied by two terminal pedicellate spikelets. The length of the raceme varies according to the number of nodes and the length of the internodes. Some species have one to four nodes and others four to eight. Internode length, thickness, and hairiness also vary from genotype to genotype.

Sessile spikelets. The shape of sessile spikelets ranges from lanceolate to almost round or ovate. Sometimes they are depressed in the middle. At flowering they are green but then change shades, becoming straw- or cream-colored buff, yellow, red, brown, purple, or almost black at maturity. There are two glumes which vary from hairy to nonhairy. The glumes are hard and tough with nerves, and are obscure except near the tip. In some species, the glumes are thin and brittle, while in others they are thin and papery. The lower glume is enclosed by the upper glume with its membranous margin. The lower glume is usually flat and conforms more or less to the shape of the spikelet. The upper glume is more convex or boat-shaped. The seed may be enclosed by the glume or may protrude from it either partially or completely. The number of sessile spikelets in a single inflorescence of cultivated sorghum varies from 2000 to 4000 (House 1985).

There are two lemmae, composed of a delicate, white, thin, and papery tissue. The lower lemma is elliptical or oblong and equal in length to the glume. The upper lemma is short, ovate and may be awned. There are two lodicules and a palea. The spikelet has two pistils and three stamens. The stigma is fluffy, attached to a short style extending to the ovary. The anthers are attached to long, thread-like filaments.

Pedicellate spikelets. These are narrower than the sessile spikelets and are lanceolate. They may be smaller or longer or of the size of the sessile spikelets. They are male or neutral, or may rarely have a rudimentary ovary. The lemmae are short and the upper lemma rarely has an awn. Three stamens and two lodicules are found between the lemma and the palea. The lodicules at the base of the floret are truncate, fleshy, and ciliate.

Flowering

Floral initiation in cultivated sorghum starts 30-40 days after germination. The initial flower develops into an inflorescence. About 6-10 days before flowering, the boot forms a bulge in the sheath of the flag leaf. Sorghum usually flowers in 55 to 70 days in warm climates (House 1985), depending on the genotype.

Two days after the emergence of the inflorescence from the boot, the flowers begin to open. The flowering starts in the sessile spikelets at the tip of the inflorescence and progresses toward the bottom over 4 or 5 days. It takes 6 days for the whole inflorescence to complete flowering. The maximum flowering takes place on the third or fourth day. At flowering, the glumes open, and the three anthers fall free, while the two stigma protrude, each on a stiff style (House 1985). As the stamens emerge out of the opening glumes, they rotate and spread outward. The filaments elongate rapidly and the anthers become pendent. When flowering of the sessile spikelets is halfway through on the inflorescence, the pedicellate spikelets start opening from the tip and proceed downwards, completing flowering earlier than the sessile spikelets in the inflorescence. The time taken from the commencement of glume-opening to completion of its closing is about 1-2 hours, which varies from cultivar to cultivar.

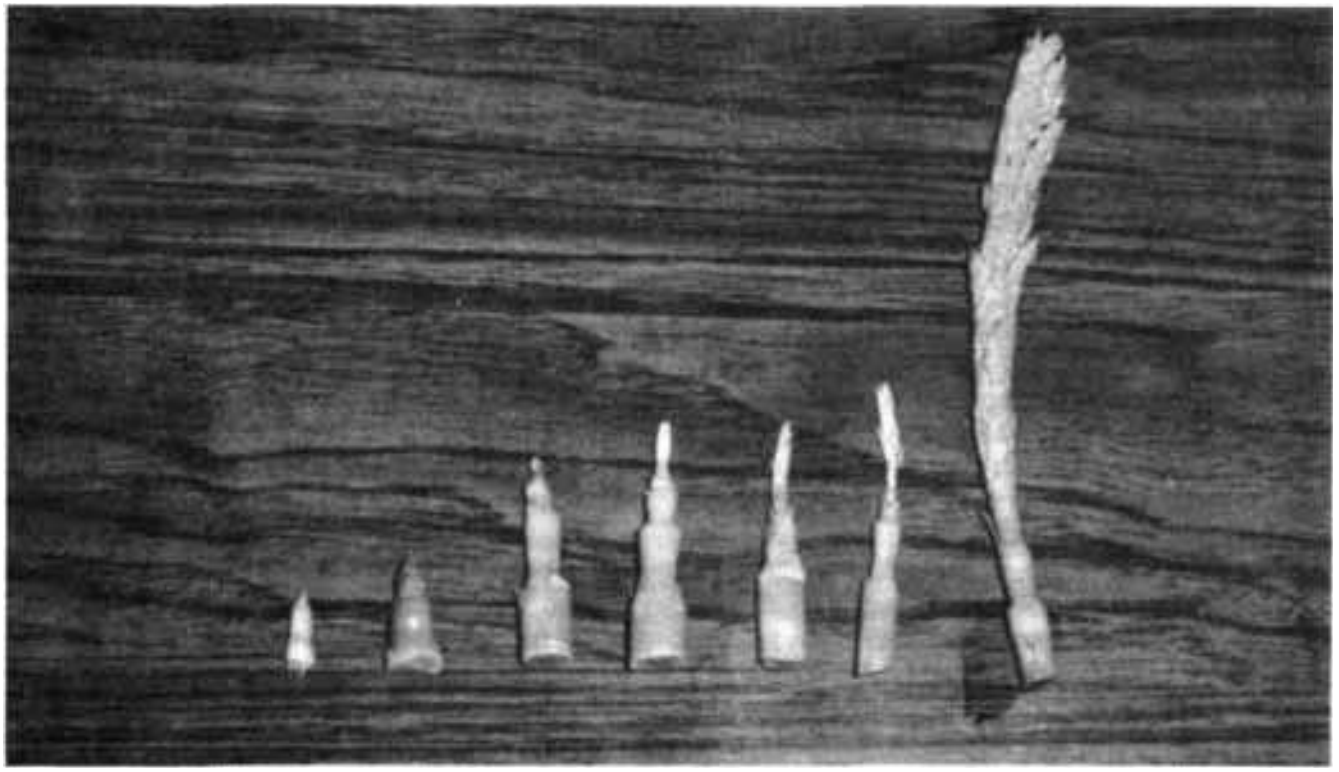


Figure 3. Gradual primordial differentiation into sorghum inflorescence.

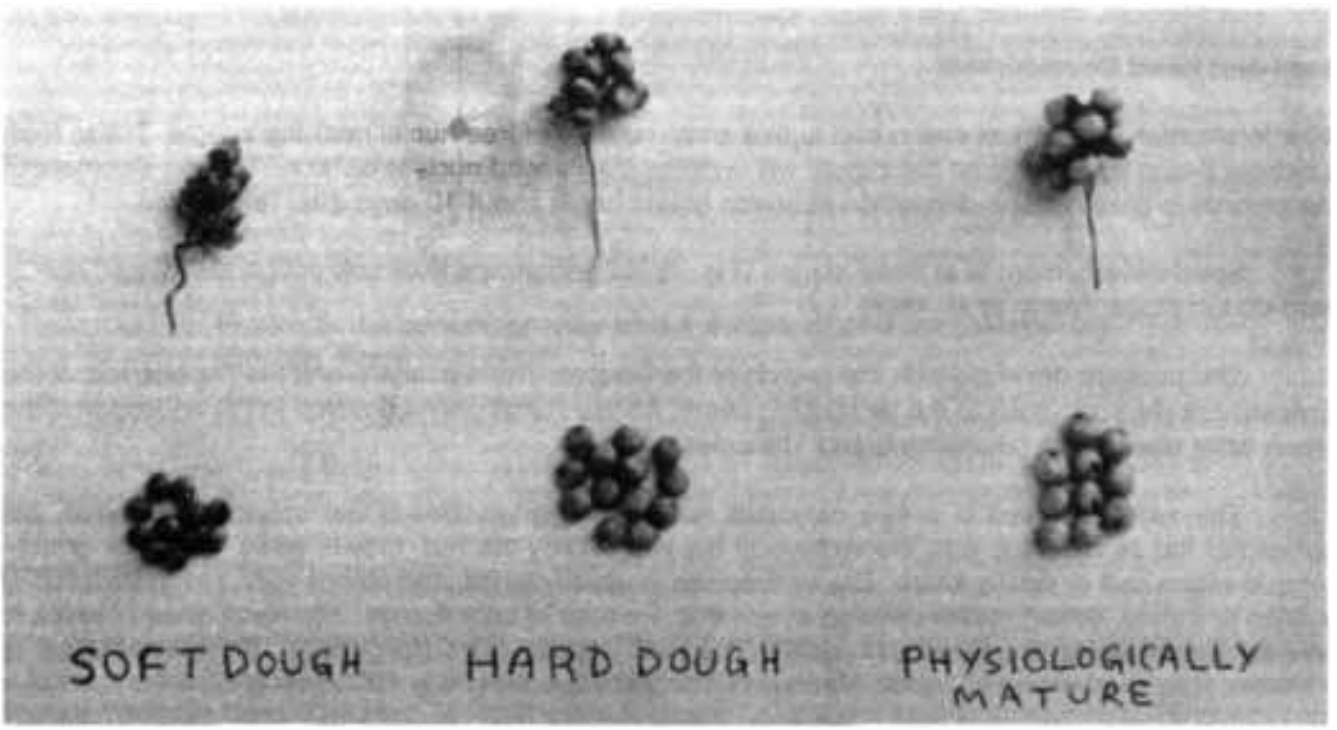


Figure 4. Stages of sorghum seed development.

Flowering starts at midnight and continues up to 1000 depending on the genotype and climate. The maximum anthesis is between 0600 and 0800. Wet and cool weather delays flowering. The anthers dehisce when they are dry and the pollen grains are ejected into the air and onto the stigma. Sorghum is primarily self-pollinated (cross-pollination is only 2 to 10 percent). The florets of some of the very-long-glumed types do not open for outcrossing to take place, a phenomenon called cleistogamy. The discovery of cytoplasmic male sterility in sorghum has made it possible to produce commercial hybrid seeds. A good male-sterile plant does not develop anthers, or the anthers remain shrivelled without pollen (House 1985).

Pollination and Fertilization

Flower-opening is facilitated by the swelling of the lodicules. When stigma becomes visible, the stamen filaments elongate and the anthers become pendent. This process takes about 10 min. The flower remains open for 30 to 90 min. After the anther dehiscence, the pollen shedding is through the apical pore. The stigma is pollinated before the emergence of the anthers from the spikelets. When pollen grains land on the stigma, they germinate immediately and develop pollen tubes, each with two nuclei, one vegetative nucleus and two sperm nuclei. One sperm nucleus fertilizes the egg to form an embryo (2n) and the other nucleus fuses with the polar nuclei to form the endosperm (3n). Sorghum has a 20-chromosome complement. After pollination the glumes close, though the empty anthers and stigmas still protrude. The pollen retain their viability for 5 h at room temperature. In refrigerator the pollen retain their viability for 3 to 4 days (Sanchez and Smeltzer 1965). The pollen require light to germinate (Artschwager and McGuire 1949). The stigma remains receptive for 10 days.

Under normal conditions on receptive stigma fertilization takes place in 2 h. Organ differentiation occurs the following 12 days, and the embryo continues to grow until the seed is mature (Schertz and Dalton 1980).

Seed and Seed Development

After fertilization, the endosperm nuclei form a small number of free nuclei near the zygote. These form a cellular tissue by which time the zygote will undergo the second nuclear division. The development of the embryo is gradual. The deposition of starch grains begin about 10 days after fertilization.

Seed development is in three stages (Fig. 4): milk stage, early or soft-dough stage, and late or hard-dough stage (Murty et al. 1994).

The pericarp develops with the growth of the embryo. The mesocarp and the hypodermis of the pericarp are chlorophyllous in the developing ovary. As the starch grains develop in the endosperm, the green color disappears (Sundararaj and Thulasidas 1980).

The sorghum seed is a free caryopsis, also called grain. Seeds are spherical in shape, but somewhat flat on one side with the embryo at the base. They are red, brown, white, yellow or cream-colored with a dull or pearly lustre. The endosperm is usually white, sometimes yellow. The nucellus is hyaline or brown. Brown nucelli develop seeds that are poor in appearance. The testa when present, is colored and contains tannin (House 1985). The seed shape varies from ovate, obovate, elliptical to orbicular. The seed size also varies from small, medium, to bold (1-6 g $100'^{1}$ seed).

The seed consists of three parts (Fig. 5): pericarp (outer coat, 6% by weight), endosperm (storage tissue, 84%), and embryo (germ, 10%). The pericarp is thin unlike the mesocarp which has

many layers. The grain is composed of the embryonic axis and the scutellum.

Embryo is made up of 70% fat and 13% protein in the grain. The endosperm varies from comprising 100% soft tissue with a little corneous portion to a solid corneous seed. It contains a layer of aleurone cells, the outer corneous endosperm surrounding a central floury endosperm.

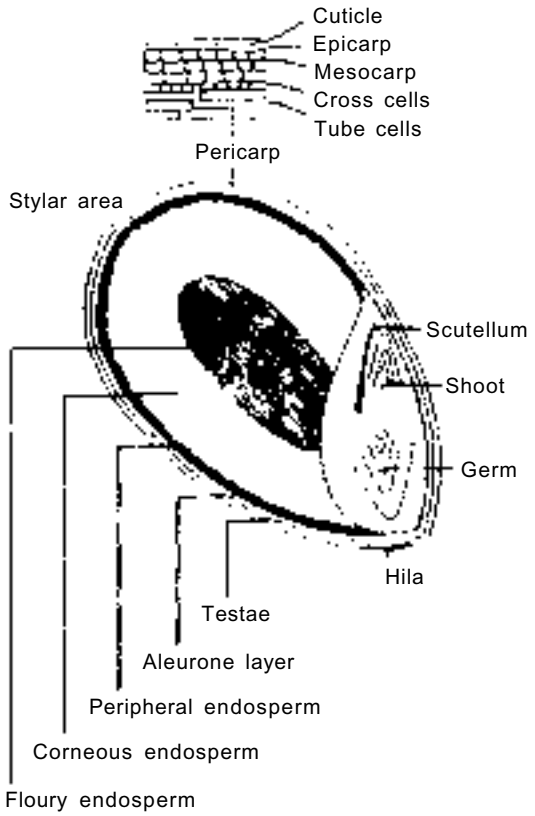


Figure 5. Longitudinal view of the structure of a sorghum seed.
(Source: Murty et al 1994)

Physiological Maturity

The grain matures in 30 to 35 days after fertilization. At physiological maturity a dark brown callus tissue is formed at the base where the seed is attached to the spikelet. This callus tissue stops the translocation of nutrients from the plant to the seed. At physiological maturity, the seed contains 25 to 30% moisture and is fully viable. For safe storage, seed moisture should be brought down to 10-12%.

Sorghum Plant and Flower Parts

Belum V S Reddy

The previous chapter dealt with the theoretical aspects of sorghum growth and development. This chapter will demonstrate the growth stages of sorghum, and its floral parts.

Germination, Seedling, and Panicle Development Stages

- When a seed is sown in moist soil, it swells due to moisture absorption. The seed coat breaks and a small coleoptile and a primary root (radicle) emerge. The coleoptile first appears above the ground in 3-10 days, depending on temperature (Fig. 1).

- As the young plant begins to grow, adding more leaves, the coleoptile remains as a sheath at the base of the plant.

- The mesocotyl grows, and a node is formed at the base of the coleoptile.

- Secondary roots begin to grow from this node, 3-7 days after the plant emerges from the soil. The primary roots die, and branch roots may develop on the lowermost nodes.

- The major root system develops from the secondary or adventitious roots.

- Leaves/nodes develop at the rate of one in 3-6 days; the plant remains in a vegetative phase for 30-40 days, during which all leaves (12-18) are formed. The seed has 6-7 embryonic leaves.

  - The culm or stem is made up of a series of alternating nodes and internodes.
  - The stem is solid, with a hard cortex or rind, with a softer pith at the center.
  - The leaves are attached to the node, and vary in length, width, and angle of attachment.
  - Leaves are arranged alternately on the stem and have a sheath and a lamina with a ligule at the base.

- The grand growth stage is due to cell elongation.

- Floral initiation leading to inflorescence development involves:

  - elongation of the apical meristem
  - differentiation of primary-branch primordia on the floral apex
  - differentiation of secondary-branch primordia
  - development of secondary- and tertiary-branch primordia
  - elongation of the panicle
  - formation of the panicle branch (raceme)
  - formation of fertile (sessile) and sterile (pedicellate) spikelets on the racemes.

- The panicle has a central axis. There are many secondary and tertiary rachises, which bear the racemes (Fig. 2).

- Each raceme always consists of one or several spikelets; one spikelet is always sessile and the other pedicellate, except for the terminal sessile spikelet, which is accompanied by two pedicellate spikelets.

- Sessile spikelets (seed-bearing) (Fig. 3) consist of:

  - an outer glume (convex or boat-shaped) and an inner glume (flattened); glume texture, size, and thickness are variable. The seed is enclosed by the glume or protrudes from it depending on the race of sorghum.
  - two lemmas consisting of delicate white tissue; the lower one is oblong or elliptical, equal in size to the glume; the upper one is shorter and ovate, and may be awned.
  - two lodicules, much reduced, useful in flower opening.
  - a palea, much reduced, of little interest.
  - two pistils/stigmas, attached to a short, stout style extending to the ovary.
  - three thread-like stamens, attached to the anthers.

- Pedicellate spikelets:

  - much narrower than the sessile spikelets, lanceolate in shape.
  - male or neuter, but may *very* rarely have a rudimentary ovary.
  - lemmas are much reduced in size.
  - the upper lemma rarely has an awn, depending on the genotype.

- Flowering (opening or protruding of anthers and stigmas) begins at the tip of the panicle and proceeds toward the bottom. It usually takes 4-12 days for all the florets to flower.

- Seed or caryopsis:

  - spherical in shape or somewhat flattened on one side, depending on the race (Fig. 4).
  - pericarp color varies (red, brown, white, yellow, cream-colored).
  - testa may also be colored (dark red to brown).
  - endosperm may be white or yellow (carotenoid pigments that have a relatively low vitamin A activity).

Flower Opening/Anthesis—A Discussion

Anthesis refers to the period of flower opening during which the spikelets are open, the anthers are extended, and the pollen sacs burst to release pollen.

Flowering of sorghum inflorescence normally starts as soon as the peduncle completes its elongation (House 1985). Blooming of the spikelets progresses from the tip to the bottom of the panicle in a fairly regular manner, with the spikelets in the same horizontal plane across the panicle opening at the same time.

Flowering of the inflorescence may be spread over a period of 4-13 days depending on the cultivar, panicle size, temperature, and humidity. In cooler weather (Dec/Jan at ICRISAT Asia Center, Patancheru), completion of panicle flowering takes about 10-13 days. The two lodicules at the base of the floret first swell and exert pressure on the glumes, forcing them to open in about 10 min. This usually happens between 0200 and 0800.

Figure 1. Germination and seedling growth in sorghum (1-7 days).

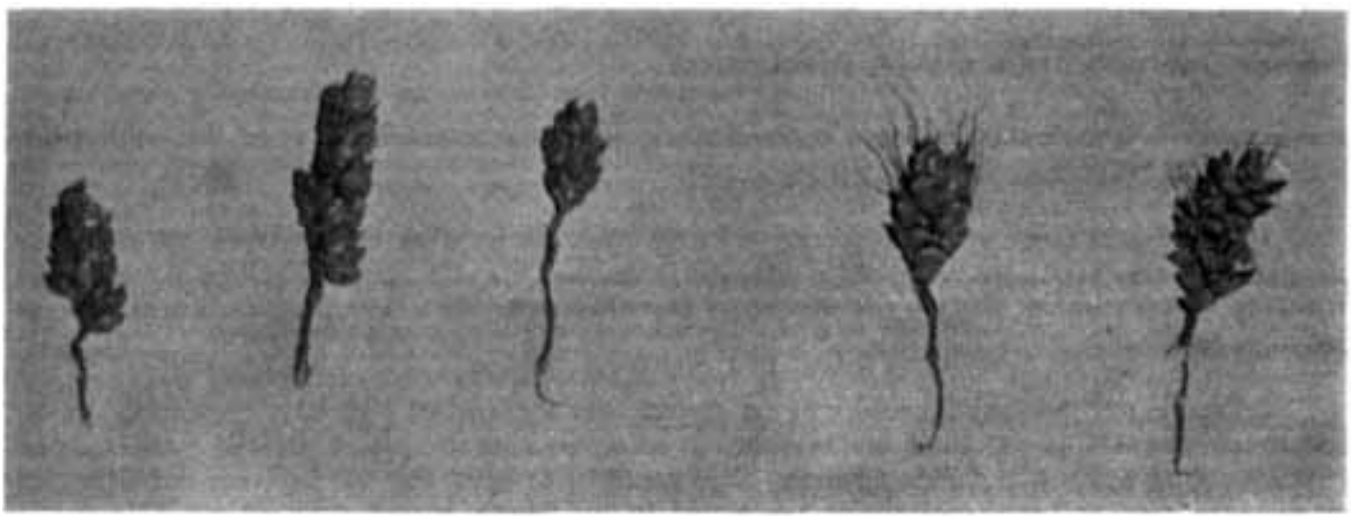


Figure 2. Sorghum racemes.

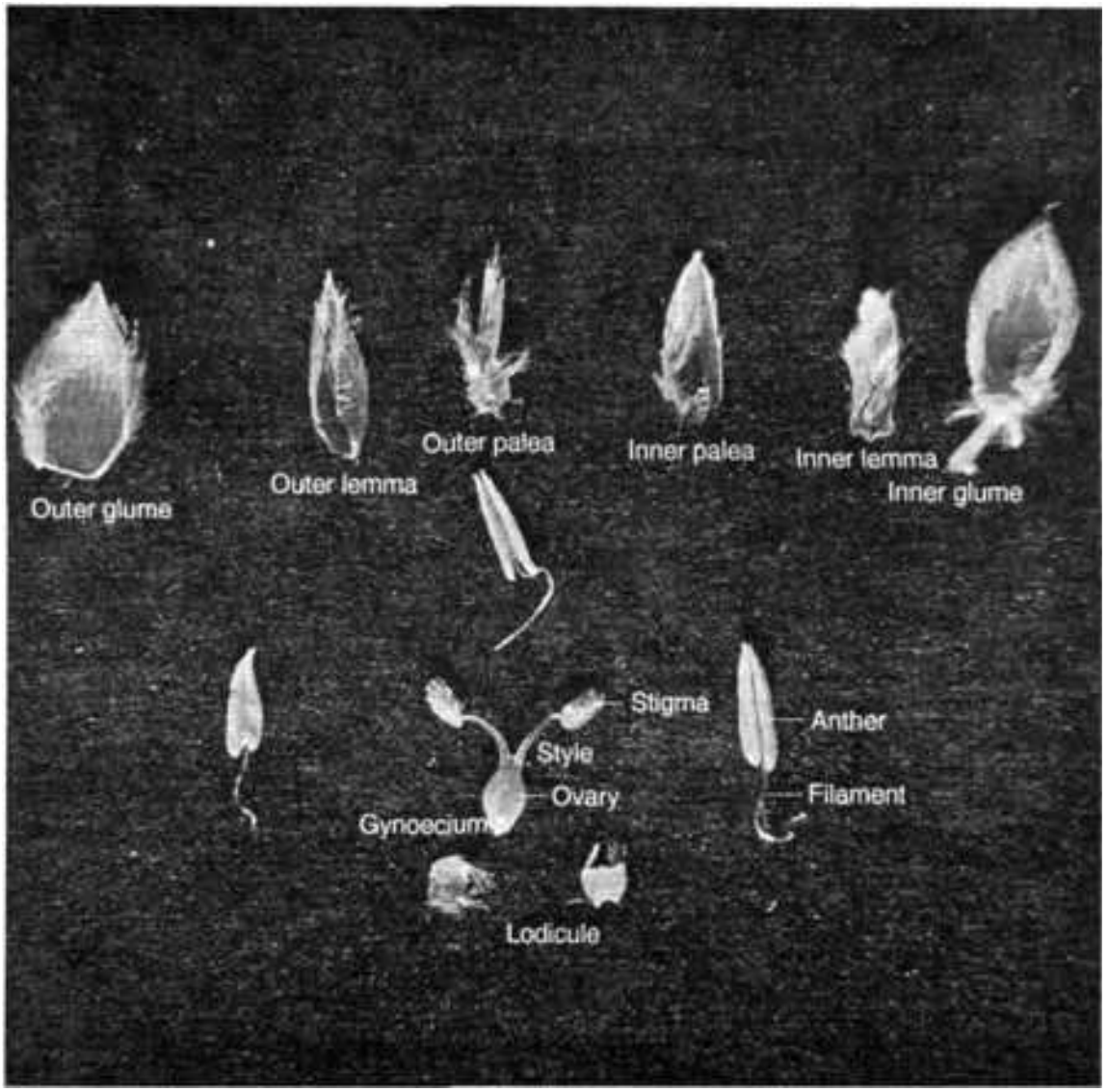


Figure 3. Parts of sessile florets in sorghum.
(Source: Murty et al. 1994)

Usually, the anthers protrude first and then the stigmas. This condition is called protandry. However, there are cultivar differences in which the stigmas and anthers emerge together or one precedes or follows the other. For example, in the zera-zera-derived cultivar ICSV 112, the anthers come out first, while in the line 296 B, the stigmas protrude first soon after anthesis. In Bulk-Y, the stigmas come out much earlier than the anthers. The filaments enlarge rapidly as the glumes open, and the anthers become pendent.

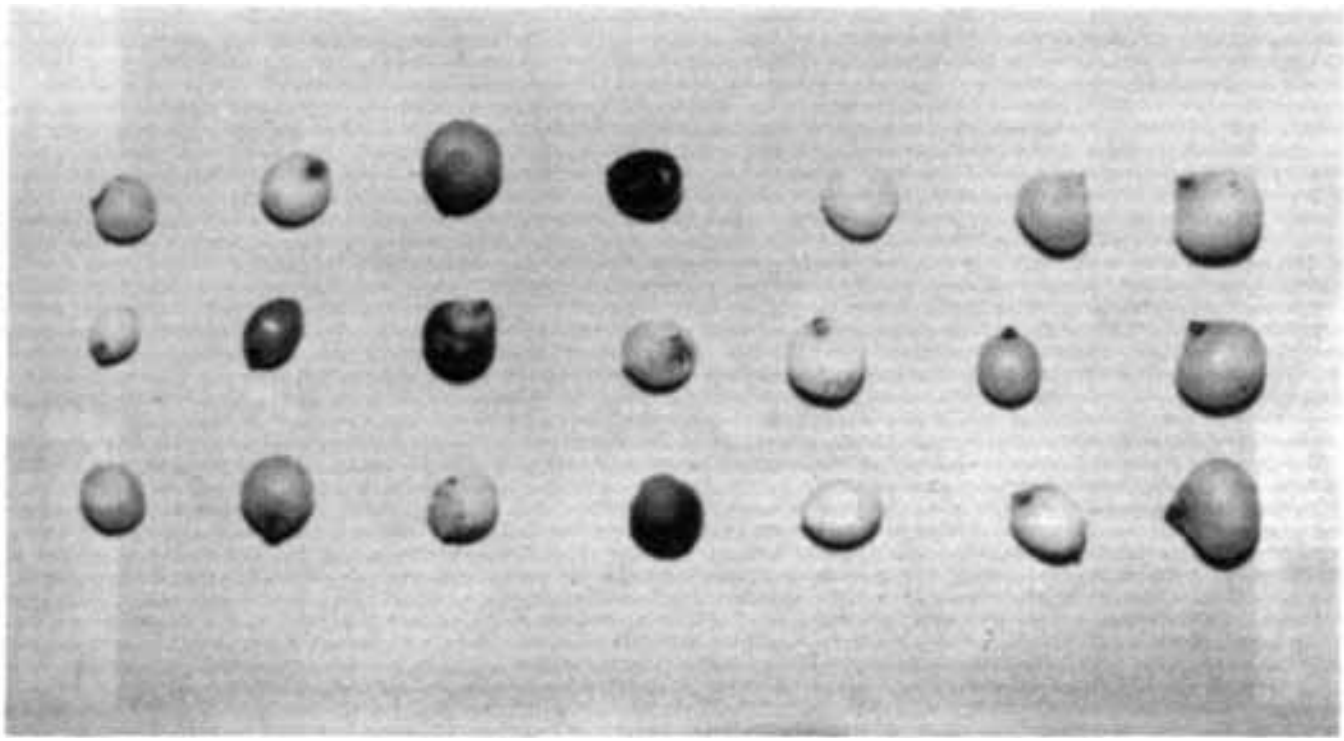


Figure 4. Variation in the size and shape of sorghum seed.

The time from the commencement of glume opening to completion of closing is about 1 -2 h, which varies from cultivar to cultivar. Anther opening and shedding of pollen, called dehiscence, and the time of its occurrence depends greatly on the weather conditions; in the tropics, dehiscence occurs at around sunrise on clear days. If the weather is damp or cool early in the morning, it can be delayed until 1000 h. Usually, the sessile (fertile) spikelets open first; the pedicellate spikelets start opening a few days later, but the anthesis of pedicellate spikelets is completed in the panicle much earlier than the sessile spikelets.

Selfing and Crossing Techniques in Sorghum

Belum V S Reddy

Biological variation is the basis of evolution. Plant breeders use this variation to direct and control evolutionary processes in order to develop new cultivars. Selfing and crossing are essential tools in the regulation of variability in plant breeding programs. The breeder must therefore know these techniques.

Importance of Selfing and Crossing

When a flowering panicle is tapped with a finger, a cloud of yellow pollen grains can be seen. The wind carries the pollen grains to the stigmas, and pollination is achieved. Pollen is normally viable for 3-6 h in the anther, and 10-20 min outside. In nature, occurrence of outcrossing varies from 1 to 10%; in wild types with loose/open panicles, it may be up to 30%. In normal compact or semicompact panicles in improved cultivars, selfing can be up to 90-95%, with 5-10% outcrossing, occurring more frequently at the tips of the panicles.

Selfing and crossing or outcrossing are processes with opposite effects. Selfing promotes homozygosity and preserves the linked-gene complexes, which helps to maintain pure stocks of cultivars. Outcrossing or crossing promotes recombination and creation of new linkage gene complexes, leading to variability, which provides an opportunity to the breeder to select upon.

Techniques of Maintaining Genetic Purity of Seed Stocks

Various techniques are followed in breeding programs to maintain/enhance the purity of seed stocks. The choice of the methods depends on the quantity of seed required, the resources available, and the extent of genetic purity and trueness-to-type required for the given material. These methods are described briefly here.

Roguing. This method is followed when complete purity is not a must, and when the breeder is faced with a large number of lines with limited resources and personnel. Before flowering, all odd plants or 'rogues' are removed. The panicles, after trimming the tips (top quarter of the panicle), are harvested and bulked from the plots in breeding blocks. This method does not assure genuine purity of the stocks. Therefore, when a crop is raised from seed multiplied in this manner, roguing should be repeated.

Isolation. When one or two stocks need to be multiplied in large quantities, sowing in isolation—field plots away from other sorghum plots, with or without variable sowing times—is desirable to maintain a high level of genetic purity. Isolation with variable sowing times is risky as there is a chance of overlapping of flowering between different plots. Isolation that physically separates plots is considered more useful. A minimum distance of 200 m between sorghum plots is recommended for multiplying varieties or pure lines with the required standards of genetic purity. Generally, in India, seed certification standards call for 99.5% genetic purity. Roguing of 'odds' or 'rogues' before and during flowering is essential, and plants with trueness-to-type should be retained/harvested.

Selfing by bagging. Sorghum is a perfect-flowered plant (i.e., it has both sexes in the same floret). Self-pollination or selfing is the process of ensuring the transfer of pollen of a floret to the stigma of the same floret or of another floret within the same panicle. This is usually accomplished in a breeding program by using kraft paper bags. These come in varying sizes (14 cm x 6 cm x 37 cm or 14 cm x 6 cm x 42

cm). The choice of the size depends on the potential size of the panicle when it starts developing grain after flowering.

In addition to kraft paper bags, the other things required for selfing are a pair of scissors, paper clips or a stapler, watchmaker tags, and a marker. The steps involved in selfing are:

1. Remove odd or off-type or rogue plants from the plot before they reach the boot leaf stage.

2. When a few florets have opened at the tip of the panicle, snip off the flowered florets.

3. Cut the flag leaf at the base.

4. Record the date of selfing on the selfing bag.

5. Put the bag (with the date) over the panicle, taking care to see that the whole of the panicle is covered by the bag, and that the bag also covers about 5-8 cm of the peduncle.

6. Make sure the peduncle stays in the center of the mouth of the bag wrapped over by the folded corners of the paper bag on either side.

7. Either staple the folded corners of the paper bag or put a paper clip, taking care to see that the bag holds the peduncle tightly.

Ten to 15 days after bagging, the bags can be removed from the panicle. The same bags or watchmaker tags can be stapled around the peduncles to mark selfing. The number of plants *to* be bagged in a plot to ensure selfing depends on the purpose of developing materials (in case of segregating lines), and the quantity of seed needed (in case of near uniform lines). Care should be taken to harvest individual plants separately in case of segregating generations, and bulk harvest the true-to-type panicles only in case of uniform lines.

Precautions. Bags can be blown away by the wind or can be damaged by rain. Care must be taken to replace them immediately, recording the information originally written on the bags. Periodic inspection of the selfed plots is essential to detect damaged bags.

Techniques of Hybridization

Outcrossing, referred to as crossing here, is a process of transferring pollen grains from a floret of one panicle to the stigma of a floret of another panicle. In nature, it is usually effected by the wind as stigmas remain receptive up to a week or more after blooming, depending on the temperature and humidity. Lower temperatures (as in December at IAC) favor a longer period of receptivity of stigmas. However, stigmas are most receptive during the first 3-5 days after their emergence.

Breeding, as mentioned earlier, is directed evolution, which allows variability. The gain from breeding is directly proportional to the amount of useful variability created by crossing two or more parents.

Hybridization of sorghum on a field scale is made feasible through the use of the genetic and cytoplasmic-genic male sterile (CMS) system. There are a number of genes (ms_1, ms_2, ms_3, ms_4, ms_5, ms_6, ms_7, and ms_8) which individually contribute in homozygous condition to male sterility. Also, another

system, independent of the genetic system, called the CMS system, creates male sterility because of the interaction of genes in the cytoplasm with those in the genome. This system will be discussed in the next chapter.

In addition to this, there are other techniques of hybridization which do not involve the male sterile system. These are explained below in detail.

Emasculation with Hot Water and Plastic-Bag Technique

Items required. Plastic sleeves, a pair of scissors, string, butter-paper bags, paper clips or a stapler with staples, hot water in a thermos flask, and a thermometer.

Procedure. The steps involved are:

1. Cut and trim the florets at the tip of the panicle. Take a bag made out of a plastic sleeve and tie it closely around the peduncle to surround the panicle.

2. Pour hot water (42°C) into the closed plastic sleeve and leave it for 10 min, soaking the panicle in hot water.

3. The water is drained after 10 min, and the sleeve is tied over the panicle.

4. The florets at the top of the panicle open after 2-3 days and anthers emerge but do not dehisce and do not shed pollen; knock these anthers free from the panicle by tapping it.

5. Remove the remaining unopened florets from the lower portion of the panicle.

6. Get pollen from another panicle of the desired line in a butter-paper bag and put it over the emasculated panicle, tying it around the peduncle as in the selfing process.

7. Before collecting the pollen, write the name of the pollen parent and the date of crossing/pollination on the bag.

8. On the fourth day after pollination, check for selfed florets; these can be recognized by their distinctively superior size compared with the rest. Remove the selfed florets and rebag.

(Note: This is a cumbersome method and requires a lot of preparation. It leaves some selfs in the F_1 which need to be thoroughly checked and rogued out. It is always safer to follow the hand- emasculation method which can be easily done by unskilled staff with some training.)

Hand Emasculation and Pollination

Conventional crossing or hybridization of different sorghum varieties is carried out by simple hand emasculation of normal bisexual florets, and then transferring the pollen from the chosen male parent (which usually is a pure line but not necessarily always) to the stigmas of the emasculated florets.

Items needed. A pair of scissors, a secateur or a manicuring clipper, a blunt needle or a pencil, a pair of forceps, 7 cm x 3 cm x 15 cm butter-paper bag, paper clips or a stapler, and a marking pen.

Procedure. The steps involved are:

1. From the desired parental line, choose a panicle that has just started anthesis.

2. Clip off the florets which have completed anthesis, with a secateur or scissors.

3. Remove primary- or secondary- and tertiary-branch rachises in the lower portion of the panicle, leaving about 200-300 florets in the central portion of the panicle just below the clipped florets.

4. Clip off all the pedicellate (sterile) florets from the central portion, leaving only the sessile (fertile) florets.

5. Thin out the sessile florets by clipping off some of the tertiary rachises to make it easier to hold the sessile florets during emasculation.

6. Grasp the sessile floret to be emasculated between the thumb and forefinger.

7. Insert a blunt needle between the glumes below the middle portion of the floret, and move it slowly around the inner surface of the glumes so as to break the stamen filaments.

8. Lift the needle out and upwards, slowly pushing the detached anthers out of the floret.

9. After emasculating the florets as described above, cover them with a butter-paper bag and clip or staple it as explained earlier in the selfing process. These bags should have the date of emasculation recorded on them.

10. Inspect the emasculated panicles on the following day for any remaining anthers that might have emerged from the florets. Remove these florets along with the anthers, and once again cover the emasculated panicles with bags.

11. On the third/fourth day after emasculation, take the pollen from the chosen parent into another butter-paper bag. Slowly insert the emasculated panicle into the bag with the pollen, and with a hand over the bag clasping the peduncle at the base of the panicle, shake the panicle so that the pollen in the bag stick to the stigmas that would have emerged from the emasculated florets.

12. Staple/clip as in selfing with the folded corners of the mouth of the bag clasping the peduncle. Make sure that the bag carries information on the date of emasculation, date of pollination, and the male parent used in crossing. It is useful to pollinate a second time on the following day to ensure pollination of all the florets.

When the seed is harvested from the pollinated panicle, make sure that the bag containing the seed is properly labelled and the male and female parents and the crosses are clearly indicated. The cross is usually denoted as follows:

Name of the parent female x male, where 'x' denotes the cross. For example, IS 3541 x IS 1052 means that IS 3541 as female has been crossed with IS 1052 as male.

Precautions. Care should be taken that the glume closest to the pedicellate spikelet is held facing away from the worker. Trimming should be done so that the individual sessile florets remain uniformly spread

along the panicle branch.

Fertilization

Pollen grains germinate as soon as they come in contact with a receptive stigma; the pollen tubes grow through the stigmatic papillae down to the ovary through the stylar region. Only one pollen tube succeeds in reaching the micropyle. The sperm nucleus divides into two, one of which fertilizes the egg cell to give rise to the embryo (2n = 20 chromosomes in sorghum), the other joins the two polar nuclei to form the endosperm (3n = 30 chromosomes, i.e., 20 from the female parent and 10 from the male parent). This process of embryo formation by the union of egg nucleus and sperm nucleus is called fertilization. The glumes close shortly after pollination. The ovule begins to develop as a light green, almost cream-colored sphere, and about 10 days after pollination, it becomes bigger and turns dark green. The development of the embryo and endosperm continues for another 30 days when the seed reaches physiological maturity with the hilum region (a spot on the seed through which the seed receives nourishment of the plant) becoming black. During the development, the seed passes through milk, early-dough, and late-dough stages. The dried-up style may persist in some seeds up to physiological maturity (House 1985).

Development, Production, and Maintenance of Male-Sterile Lines in Sorghum

Belum V S Reddy

The emasculation and pollination techniques described in the previous chapter cannot be used for production of hybrid seed on a commercial scale. Male-sterile plants are more suitable for such purposes (House 1985). Male-sterile plants are characterized by nonproduction of functional pollen, or if pollen grains are produced, they are either ill-formed or the anthers do not dehisce (Fig. 1). Usually, the former type of male-sterile plants are recognisable in the field by their whitish, thin, and scaly anthers in contrast to the plump and yellowish male-fertile anthers. The latter group, with nondehiscent anthers, are usually difficult to differentiate on the basis of anther appearance or morphology. As a result, male-sterile systems characterized by nonfunctional pollen have been exploited widely in sorghum. This male-sterile system is attributed to two causes: male-sterile genes present entirely in the genome, or male-sterile genes present in the genome as well as the cytoplasm. The former system is called genetic male sterility and the latter cytoplasmic-genic male sterility. Genic male sterility is due to single recessive alleles in a homozygous condition. This system is not used for large-scale hybrid seed production, primarily because it requires roguing out of male-fertile plants from the male-sterile stocks. Cytoplasmic-genic male sterility is used widely in hybrid programs, and its principles are given below.

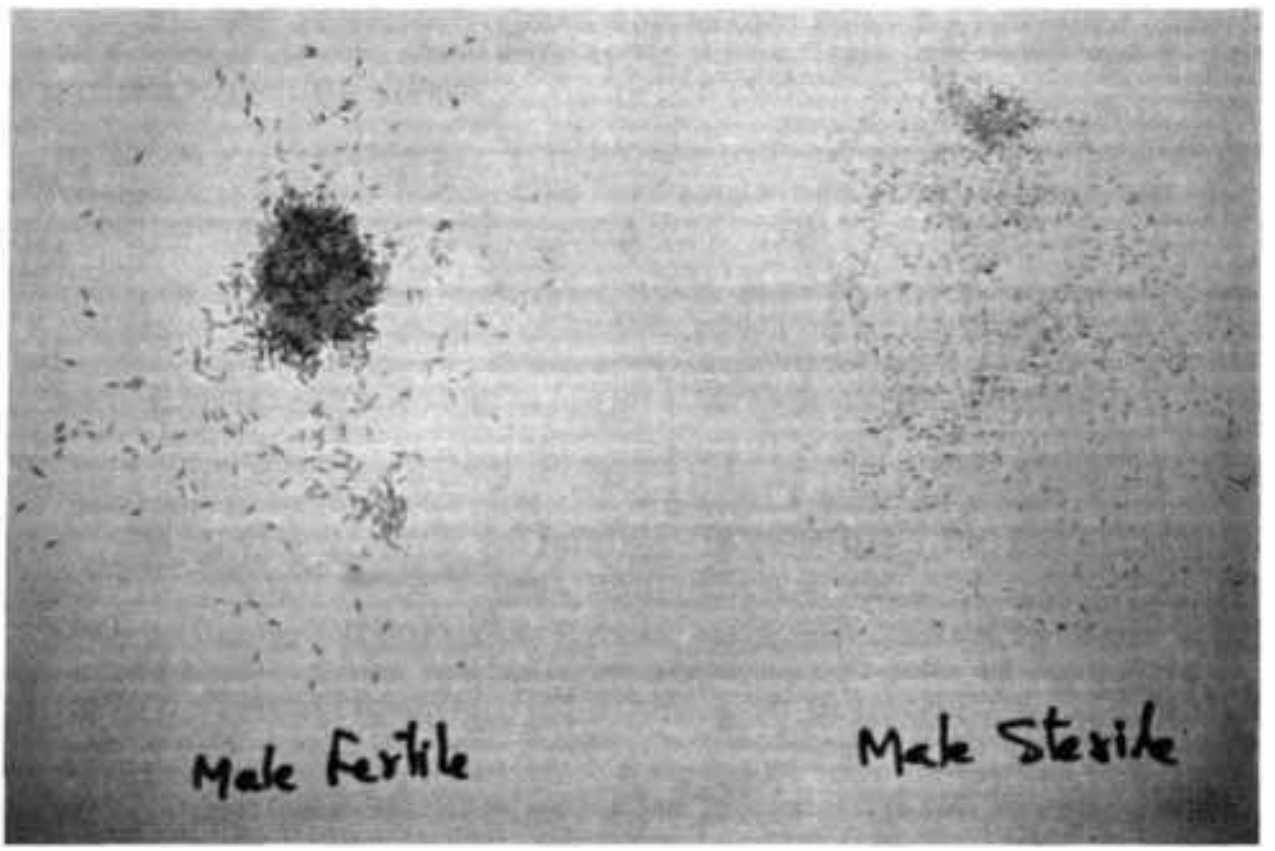


Figure 1. Male fertile (left) and sterile (right) sorghum anthers.

Cytoplasmic-Genic Male Sterility

In sorghum, Stephen and Holland (1954) discovered cytoplasmic-genetic male sterility (CMS) in the progenies of a cross between two cultivars, Milo and Combine Kafir, with Milo as the female and Kafir as the male. Male-sterile plants to the extent of 25% were observed in the F_2 generation of the above cross when Milo was used as female and not as male. The male-sterile segregants from this cross produced male-sterile hybrids when crossed with the Kafir parent and fully fertile hybrids when crossed with the Milo parent. Thus, it was recognized that Kafir could be used as a maintainer of this source of cytoplasmic-genetic male sterility. Since the progeny received the cytoplasm from the female, it was hypothesized that the Milo parent had a male sterility-inducing cytoplasm and dominant genes for pollen fertility, whereas the Combine Kafir parent contained a normal (fertile) cytoplasm but the recessive male-sterile genes. All progenies of the Milo x Combine Kafir cross contained Milo (sterility-inducing) cytoplasm, but those that also inherited the homozygous recessive genes from the Kafir parent were male-sterile. The male-sterile plants in the Milo x Combine Kafir cross were used as females in repeated backcrossing with Kafir as the male parent. At the end of seven backcrosses, the entire genome of Kafir was transferred into the Milo cytoplasm. This resulted in two morphologically similar versions of the Combine Kafir (CK 60) parent: a male-sterile Combine Kafir (CK 60A) and a male-fertile Combine Kafir (CK 60B). The male-sterile lines are designated as A-lines and their maintainer lines as B-lines.

Development of New Hybrid Parents (A-, B-, and R-Lines)

The parents that produce fertile F_1s when crossed with A-lines are called restorers or restorer lines or R-lines. The development of parents involves two steps: (1) identification of potential B- and R-lines; and (2) development of A-lines and R-lines.

Identification of B- and R-lines. Improved breeding lines, named/released varieties, and landraces form the pollinator collection, the sources that can be used as pollen parents or pollinators. The hybrids obtained by crossing these pollinators with a male-sterile line, the testcrosses, are evaluated for the sterility maintenance or fertility restoration in them (Murty et al. 1994). This evaluation is usually sown in small plots (one or two rows of 2 m length). Examination of anther morphology may be a basis for classifying the hybrids as male-sterile or male-fertile; but it is not a sure way. A more reliable method is the bagging test, i.e., covering 4-6 panicles with a paper bag before anthesis, and observing the seed-set after 2-3 weeks. (The items needed for bagging tests are the same as in selfing.) The testcrosses are of the following four types:

1. Testcrosses exhibiting absolutely no seed-set on all the bagged panicles, i.e., male sterility was maintained in these hybrids. The corresponding pollinator is classified as a maintainer or nonrestorer or B-line. This could serve as a source of a new A-line.

2. Testcrosses with complete seed-set on all the bagged panicles. The corresponding pollen parents are classified as potential restorer or R-lines. They can serve as male parents to produce hybrids.

3. Testcrosses with a partial seed-set on all the bagged panicles. The corresponding male parents are rejected from the program as they serve neither as restorers nor as maintainers.

4. Testcrosses with a full seed-set on some bagged panicles and no seed-set in others. The corresponding pollen parent of such a hybrid is said to be segregating for fertility-restoration or sterility-maintainer genes. Usually, such parents are not pursued further in a hybridization program, as they involve additional work of fixing the genes for fertility restoration/sterility

maintenance.

Development of new A- and R-lines. Three criteria are used in the selection of parents for this purpose: genetic diversity, the *per se* performance of the lines, and the average performance of a line in crosses with other lines [called general combining ability (GCA)]. Experience in sorghum has shown that parents of diverse origin produce highly heterotic hybrids. It has also been found that the *per se* performance of parents is positively correlated with the performance of the hybrids (Murty et al. 1994). Further, the general combining ability is more important than specific combining ability (the deviation from performance predicted on the basis of general combining ability) in sorghum. Further, shorter (usually 1.25-1.75 m) and high-yielding lines with sterility-maintenance ability are chosen for conversion into male-sterile lines. Taller lines (usually 1.75-2.50 m) with restorer reaction are chosen as R-lines.

The maintainors identified through the bagging test possess recessive genes for fertility restoration/sterility maintenance but have a normal cytoplasm. The selected B-lines can be crossed with any recognized male-sterile line. The resulting F,s and the corresponding maintainers are sown alternately in small plots, and the hybrids are backcrossed repeatedly with the respective maintainer lines for six or seven generations using the corresponding maintainer lines as recurrent parents until male-sterile lines with appearance identical to the recurrent B-line parent are obtained. It is important that plant-to-plant crossing should be attempted in the backcrossing phase. This involves crossing individual male-sterile plants with individual plants of the recurrent parent that are morphologically similar to each other. This plant-to-plant method is useful to select out the partial sterility maintainers from the program. Also, it enables faster realization of A-lines with morphological traits similar to the maintainer line.

The A-lines thus obtained may be sown alternately with the respective B-lines, and the pollen (bulk) from the respective B-lines collected in separate bags may be put over the male-sterile panicles with emerged stigmas. The bags should be shaken thoroughly as in the outcrossing program explained in the previous chapter. Before pollination, these male-sterile panicles should be bagged as in selfing to prevent outcrossing with pollen from unwanted parents. Similarly, the B-lines should be selfed. The seed bulked within the A-lines will form the A-line seed. The B-line seed bulked within the line will form the B-line seed. Thus A- and B-lines are maintained. It should be remembered that roguing should be carried out before selfing/pollination of A-/B-lines.

Once uniform A- and B-lines are produced, the stability of the male sterility in the A-lines may be evaluated by sowing them in areas where the temperature at flowering reaches 42°C or more. Unstable A-lines become fertile at this temperature.

Production of A-, B-, and R-Lines

Small-scale production. R-line seed (identified through the bagging test of testcrosses) may be produced by sowing the seed in a plot of the desired size and selfing the plants after roguing out the off-types before and at flowering. Bulk harvesting of true-to-type panicles may be done. A plot of two rows of 4 m length, if maintained properly, may give about 2.0-2.5 kg seed.

Production of A - and B-lines involves several operations:

1. Sow A- and B-lines in the plot side by side. Usually, for every four rows of A-line, two rows of B-line are sown.

2. Carry out roguing regularly in the A-lines and B-lines before and during anthesis. Apart from off-types, pollen 'shedders' can be a problem in the A-lines [a pollen shedder is a fertile plant in the A-line that results from a breakdown of male sterility; in practice, however, B-line (fertile) plants which appear in the A-line plot due to mechanical mixing are also referred to as shedders]. These should be removed by inspecting the field everyday during anthesis.

3. Prune the florets of A-line with protruded anthers/stigmas at the tip of the panicles, and pull kraft paper bags over the panicles with the date of bagging recorded on them. Carry out a similar operation on the B-line.

4. After 4-6 days, collect pollen from the B-line panicles into the same bags used for selfing, and put these bags carefully over the respective A-line panicles, by slightly bending the A-line, and shake the panicles along with the pollen bags by holding the mouth of the bag tightly wrapped around the peduncle. Each pollen bag may be used to pollinate 2-3 panicles of the same A-line.

5. Cover the pollinated panicles with the same pollen bag or with a new one. The bag should carry information on the date of the first bagging and pollination, and an A x B mark indicating that it was pollinated by a B-line.

6. Pollination of A-lines with B-lines may be repeated again after the 6th or 7th day in order to pollinate all the florets in the entire panicle.

7. B-line panicles should be selfed by bagging after using their pollen to pollinate the A-line panicles.

8. Take out the bags 15-20 days after pollination/selfing, and staple them over the peduncle below the base of the panicles, as in selfing.

9. Rogue out plants at the time of harvest, and bulk harvest the panicles in A-lines and B-lines separately and label them clearly.

Precautions. Periodic replacement of damaged bags is essential.

Large-scale production. Large-scale production of A-, B-, and R-lines is usually taken up in isolation plots (Chopra 1982).

1. **Production of R-line.** R-line is produced in an isolation field separated from other sorghum fields by at least 300 m. Periodic roguing of the off-types is essential. Bulk harvesting is done by taking true-to-type panicles.

2. **A- and B- lines.** Production of A- and B-lines is done by growing the A-line in four rows alternating with the corresponding B-line in two rows. Across all the rows in the entire field, it is recommended that a strip of 1 m length should be sown with the B-line. This is useful in providing pollen to the A-line panicles at the end of the rows. Roguing of the off-type plants and pollen shedders should be done during anthesis everyday. Open pollination by wind will ensure seed-set on the A-lines. Self-pollination takes place in the B-lines. Harvesting of A-line and B-line seed should be done separately. To avoid mechanical mixing, it is recommended that they should be harvested at different times, preferably one after the other.

Improving the B-Lines and A-Lines

We have so far dealt with the procedure of developing A-lines from the B-lines identified from the pollinator collection through testcrossing. It is important to know the procedures involved in improving A- and B-lines in hybrid programs. It involves the following steps.

1. Identify the B-line(s) for improvement and the resistance source lines for stress factors or high-yielding lines (depending on the objective) which may be fertility restorers/sterility maintainers.

2. Cross the B-line with the selected source line(s) and advance them to the F_2 generation.

3. Grow F_2 under the desired screening for resistance, and select for monogenic or oligogenic traits apart from resistance.

4. Grow selected F_3 progenies in head-to-rows under screening for stress factors of interest. Select plants with the desired combination of traits within the family selected for resistance and uniformity.

5. Testcross the selected segregants onto an A-line sown separately near the F_3 nursery under screening. Also self the selected segregants (pollinator) used in testcrossing.

6. Grow the testcross and the pollinator (F_4s) in a block near the pollinator screening block. With experience, one can usually determine the male-sterile testcrosses by anther morphology at anthesis. Otherwise one should use the bagging test to identify male-sterile plants. Repeat step 4, i.e., select families for resistance and select individual plants for crossing on the basis of agronomic desirability.

7. Backcross the male-sterile F_1 (A-line) panicles with pollen from the selected plants' (as above) individual panicles as per the procedure outlined for pollination. The F_4 families selected for resistance should be used as pollinators. Harvest the backcrossed A-line panicles and selfed pollinators' panicles individually and pair them as per the pollination done.

8. Repeat steps 6 and 7 for six to seven generations. Care should be taken at every stage in the following areas: check male sterility on the basis of anther morphology and seed-set on a few panicles under bagging; also, always make plant-to-plant backcrossing, i.e., the individual male-sterile panicles (2-3) selected for backcrossing should be similar in morphology to those individual plants of the pollinators selected for pollination.

9. At the stage when male-sterile lines resemble the respective maintainer lines and are uniform, they are called A- and B-lines. The B-lines may further be selected on the basis of their *per se* performance and resistance to the factors of interest.

10. Further selection of A-lines may depend on GCA tests for traits of interest. The selected A- and B-lines may thus be numbered with the year, followed by serial number and letters A or B to indicate male sterility or maintenance. For example, 95001A and 95001B indicate that these two represent one A and B pairs, bred in the year 1995, and the line number is 1.

11. Maintenance of the selected A-lines is done as per the procedure outlined earlier.

ICRISAT Asia Center is improving CMS lines for resistance to various yield-limiting factors (diseases: grain mold, anthracnose, leaf blight, rust, and downy mildew; pests: shoot fly, stem borer, midge, and head bug; parasite: *Striga asiatica).* Also, the Center is attempting to diversify CMS lines for earliness, grain mass, stay-green, tillering, etc. (ICRISAT 1991, 1992, 1993, and 1994).

Development, Production, and Maintenance of Restorer Parents and Pure-Line Varieties in Sorghum

J W Stenhouse

A restorer line, or R-line, produces a male-fertile hybrid when used as pollinator parent for a male-sterile line. A pure line is one which is homozygous for all loci, usually as a result of continued self-pollination from a single plant, and which breeds true for all its important traits.

Sorghum is a predominantly self-pollinated crop which suffers little inbreeding depression. As such, it is amenable to forced inbreeding to produce uniform lines that can be used in different ways. The lines may be used in their own right as pure-line varieties to be grown by farmers, or as restorer lines in crosses with male-sterile lines to produce hybrids. The relative importance of the two types of use varies according to the economic status of the target farmers and the degree of infrastructure required to carry out seed multiplication. Pure-line varieties are more common in areas where farmers are unable to invest in seed each season and where sophisticated seed multiplication and processing facilities do not exist. Hybrids are more important where farmers are affluent and can invest in seed, and where there is good seed multiplication capability.

Open-pollinated varieties rarely exist in sorghum. Landraces grown by farmers are often mixtures of inbred and partially inbred lines, and represent the nearest approximation to open-pollinated varieties. However, these are usually improved by selection and inbreeding to produce pure-line varieties before any large-scale seed multiplication takes place.

Procedures for Developing Inbred Lines

The process of developing inbred lines in sorghum usually begins with deliberate crossing of two lines with contrasting characters by any one of a number of means. The crosses are normally made by hand emasculation of one parental line and pollination by the other. They may also be made using a genetic or cytoplasmic-genetic male-sterile line as the female parent. In rare cases, they may be due to natural outcrossing. The F_1 generation of such crosses is normally uniform but the subsequent generations segregate, and selection of single plants with desirable combinations of traits can be practised. Alternatively, segregating materials from random-mating populations or from farmers' fields may form the basis for the selection of individual plants for inbreeding.

It is easy to force self-pollination in sorghum simply by placing a bag over the panicle prior to anthesis to prevent outcrossing. In early-generation materials (F_2 and F_3), such bagging is not normally practised as these generations are highly variable and the vast majority of plants are discarded. It is therefore more economical to tolerate the occasional outcrossing in the early generations than to bag all the plants. In later generations (F_4 or F_5 onwards), all plants are bagged so that individual plants are treated alike, and the effects of bagging do not interfere with selection for head and grain traits.

Selected plants from segregating progenies are advanced in a head-to-row procedure. Individual panicles are taken from the selected plants, and seed from each is sown in a single row in the subsequent season, often in a special nursery where selection for specific traits can be practised. The process of selection and headrowing of individual plants with desired combinations of characters, with or without bagging to ensure self-pollination, is repeated for several generations until the progeny that results is uniform for important traits. The line can be bulk harvested at this stage, and the bulk seed is

used to establish replicated trials to compare individual selections more critically. Replicated testing of yield or other traits can begin at any stage after progenies are reasonably uniform.

The criteria used to select plants vary from location to location. Some generally desirable traits include large panicle, good panicle exertion, appropriate time of maturity, plant height, bold grains, good seed-set, high seed number, and attractive plant type. Specific criteria, which may differ from location to location, include resistances to insects and diseases and grain quality for different end-users.

Testing Restoration Ability

Inbred lines with appropriate traits for use as restorer lines must be tested to determine their fertility-restoration reaction. Pollen from the test lines is used to pollinate one or more heads of a cytoplasmic-genetic male-sterile line. The seed produced is harvested and sown to produce a hybrid crop. One or more heads of the hybrid are bagged prior to flowering to determine whether or not the hybrid is self-fertile. Only lines which give fully fertile hybrids under bagging will be retained as restorers for wide testing in combination with different male-sterile lines to generate experimental hybrids for agronomic and yield testing. The fertility of hybrids should be tested during the season in which they will be grown, as fertility restoration can be influenced by temperature and humidity, and can differ dramatically from season to season.

Desirable Traits of Good Restorers and Pure-Line Varieties

Restorer lines are normally not intended for direct use as cultivars. Therefore, they do not necessarily combine all the traits that are favored by farmers. They combine traits that make them suitable for use as parents of hybrids. These include fertility-restoration reaction, good pollen-shedding capacity, appropriate height (usually shorter than the varieties), and good grain yield.

The ability of a line to produce good hybrids in combination with male-sterile lines is known as its combining ability. A line with good general combining ability will tend to give high-yielding hybrids with many male-sterile parents. Clearly, this is an advantageous trait in a restorer parent. It can be quantified in comparison with other restorer lines in specially designed testing schemes. In sorghum, combining ability is closely associated with *per se* performance of the line. Yield testing of the restorer lines, therefore, often substitutes for formal combining-ability tests.

Pure-line varieties are intended for use directly by farmers. They must, therefore, combine the traits desired by the farmers in the target location or area. These normally include high grain yield, stability of yield over a range of conditions, appropriate duration to maturity, plant height, resistances to endemic pests and diseases, and suitable grain and stover quality. Typically, pure-line varieties are taller than restorer lines with higher grain and stover yields.

Maintenance of Restorer Parents and Pure-Line Varieties

The procedures for maintenance of restorer lines and pure-line varieties of sorghum are essentially the same. In both cases, the process begins with planning seed requirements and projecting backwards. Using conservative estimates of yields likely to be achieved, the size of the maintenance exercise required at each stage and its timing to ensure prompt delivery of the final product is planned.

For breeder seed maintenance, a head-to-row procedure is usually followed. Individual self-pollinated panicles that are true to the type of the line are selected, harvested, and threshed individually. The seed of each panicle is used to establish a single row in the subsequent season, all the plants of which are selfed by bagging. The rows are scrutinized thoroughly to determine their trueness to type. Any lines which show variation and deviation from the descriptions are discarded. Those lines which are uniform and true to type are harvested and bulked to form the basis for breeder seed multiplication. The quantities of seed required at this stage are normally small (a few kg) and can usually be met by headrowing 100-200 plants.

The head-to-row procedure is often dispensed with by experienced breeders who are confident of the uniformity of their lines and the adequacy of their bagging procedures to prevent cross-pollination. In this case, selected panicles of the selfed true-to-type plants are bulked without going through the head-to-rows. But this is a dangerous practice, as one can never be certain that cross-pollination was totally avoided or that roguing has removed all products of outcrossing. In cases where headrowing has been dispensed with and contamination is detected, it is best dealt with by going back to the head-to-row procedure to repurify the line or variety.

When the demand for breeder seed is high and is likely to run to hundreds of kilograms or tons, large-scale multiplication of breeder seed for use in basic seed production is usually done in isolation by the breeder concerned. Usually this need not be done every year but a sufficiently large quantity can be produced to provide a buffer stock as protection against sudden increases in demand. Isolation distances must be strictly adhered to in order to prevent contamination from adjacent sorghum crops. These are recommended to be at least 300 m for other fields of grain sorghum and 400 m for forage sorghum but can be modified in the light of factors such as the prevailing wind direction and velocity, plot size, and presence of windbreaks. Strict scrutiny of the crop must be practised and rigorous roguing of off-type plants must be done before and after flowering to achieve the desired level of seed purity.

Certification of breeder seed production plots by competent seed certification authorities is required in India but responsibility for the purity of the breeder seed is more typically that of the breeder or institution concerned. Often there are no guidelines for its production.

Restorer lines and varieties of sorghum are typically pure lines that have been produced by continuous selfing of individual plants selected from segregating populations. Varieties tend to be taller and higher yielding than restorer lines which are typically dwarf. It is important for varieties to have no major weaknesses but this requirement is less stringent for restorer lines whose traits can be complemented by the traits of the male-sterile line. Maintenance of restorer lines and pure-line varieties is done by head-to-row sowing of selected true-to-type plants and rigorous elimination of variable or off-type progenies. Large-scale production of breeder seed for commercial seed multiplication is normally done in isolated plots at least 300 m away from the nearest grain sorghum fields and 400 m away from forage sorghum.

Production of Sorghum Hybrids

Belum V S Reddy

Identification of sorghum hybrids for commercial multiplication involves several steps:

- Development and production of A-, B-, and R-lines with high *per se* performance and GCA. This has been discussed in the previous chapters.
- Development and testing of experimental hybrids.
- Large-scale multiplication of the selected hybrid parents (A-, B-, and R-lines) for large-scale production of designated/selected hybrids.

Development and Testing of Experimental Hybrids

Production of A-, B-, and R-lines has been dealt with in the previous chapters. Here we deal with the production and testing of experimental hybrids.

1. Grow A-lines and R-lines side by side in a crossing block. To get 500 g of hybrid seed, a 6-row plot of 4 m length should be sown with the required R-line to supply pollen for panicles in the A-line. The A-line may be sown in 2-3 rows in a 4-m long plot.

2. At anthesis, bag the A-line and R-line panicles after pruning the florets that have protruded stigmas/anthers.

3. Rogue off-type plants before and during anthesis and avoid using them in crossing.

4. Pollinate panicles in the A-line with bulk pollen from the R-line and bag both A- and R-lines after pollination.

5. Mark the bags with the following information: date of bagging of both the A-line and the R-line, date of pollination, and identity of the R-line used in crossing on the panicles of A-line.

6. Harvest the F_1 hybrid seed from the A-line panicles and selfed seed from the R-line panicles separately, and tag them accordingly. Harvesting should be done on different days to avoid mechanical mixing.

It is recommended that in case of loss or damage or mutilation of the marked paper bags, the pollinated male-sterile panicles should be bagged and marked again. So periodic inspection of the pollinated plots should be undertaken to check for and replace damaged bags.

The experimental hybrids thus produced are evaluated in replicated trials initially at one or two locations, followed by multilocational testing of selected hybrids from this initial evaluation. Multilocational testing provides an opportunity to select 1-3 promising hybrid(s) for large-scale on-farm testing and finally for release to farmers for commercial cultivation.

During this process of production and testing of experimental hybrids, information on the following should be collected:

- Flowering behavior of R-lines in relation to the corresponding A-lines. Usually, R-lines that flower 4-6 days later than the corresponding A-lines are preferred.

- The seed-setting ability of A-lines when crossed with R-lines. A-lines with inferior (< 50%) seed-setting (when properly pollinated) should be rejected.

- R-lines that are shorter than the A-lines should be rejected, as also R-lines that are too tall. In general, the difference in height between an R-line and an A-line should be about 30 cm for higher hybrid seed production.

- R-lines with good pollen-shedding ability should be selected and poor pollen-shedders should be rejected.

Large-Scale Multiplication of Selected Hybrids

When large quantities of seed are required for on-farm trials or for commercial cultivation, seed of hybrid parents (A-, B-, and R-lines) and hybrids are produced on large plots isolated from other sorghum fields.

Seed production of hybrid parents (A-, B-, and R-Lines). This has been dealt with in the previous chapters.

Hybrid (A x R) seed production. Sorghum hybrid seed is produced by growing the designated male-sterile (A) lines (4 to 6 A-lines) and a single restorer line together in each isolation and allowing cross-pollination. The seed harvested from the A-lines is the hybrid seed. Thus the number of hybrids (seed) obtained is equal to the number of A-lines, each of the hybrids having a separate A-line as its female parent and the restorer as the male parent, which is common to all the hybrids thus produced. The area sown with each A-line depends on the quantity of hybrid seed required. This method of hybrid seed production is used for producing hybrids for on-farm testing.

On the other hand, when a single hybrid is selected for commercial cultivation, the seed is produced in large quantities by growing the designated A-line and R-lines together in an isolation field (Chopra 1982; Murty et al. 1994).

In both the situations, an isolation distance of more than 300 m is generally recommended for hybrid seed production. A distance of about 400 m is necessary if there are wild or forage sorghum fields in the vicinity (House 1985).

Hybrid seed production through the time-isolation method (to avoid overlap of flowering with the adjacent crop) may be practised at an experimental station, but is not permissible in commercial or certified seed production plots.

Male-sterile and restorer lines are sown in 4A : 2R or 6A : 2R depending on the local conditions such as wind velocity, temperature during anthesis, and the pollen-shedding ability of the R-line involved. Also, the borders on either side of the field should be sown with the R-line over a strip of about 1 m width to provide pollen to the A-line panicles at the end of the rows.

It is important, as indicated earlier, that the hybrid parents should 'nick' in their flowering when sown simultaneously. Further, information on the flowering behavior of the hybrid parents is useful in deciding the sowing dates of the isolation involved for hybrid seed production. Also, care should be taken to ensure that the seed develops and matures during a period when it does not rain and when relative humidity in the air does not exceed 50%.

It is difficult to predict the flowering time of the parents accurately, because many A- and R-lines interact with temperature and day length. The interactions cannot be predicted (day length can be calculated for a given location, but temperature cannot be predicted). So it is always advisable to stagger the sowing of R-lines, especially when they are known to flower earlier than the A-lines. For example, if the male parent is known to take 62 days to 50% flowering at a given location and the A-line 72 days, the male parent has to be sown 13-15 days after sowing the A-line. Pollen shedding from the R-line usually lasts 10-15 days. Transplanting the plants either in strips in each row or all plants in one of the two rows in the R-line is known to delay flowering by 8-10 days and thus increase the period of pollen availability; this leads to higher seed-setting on the A-line.

It is important that roguing of off-types should be done regularly before and during anthesis in both the A- and R-lines. Also, monitoring for pollen shedders in the A-line and removing them should be done without fail during anthesis. All possible precautions should be taken against seed contamination through mechanical mixing during harvesting and threshing. It is recommended that the R-line should be harvested first and removed from the field and yard before starting the harvest of the hybrid seed.

Further, the following precautions will enhance seed production:

- Selection of a field with good fertility and appropriate previous crop, preferably a legume, will be useful in achieving higher productivity of seed with good quality.

- Monitor flower-bud development 20-30 days after sowing. Differences in the time of initiation and size of panicle initially in the A- and R-lines would indicate differences in their time of 50% flowering; so hasten flowering by selective irrigation and/or application of nitrogenous fertilizers such as urea or ammonium sulphate.

- Follow uniform crop management practices to grow a good crop across the entire isolation.

- Follow plant-protection measures and control pests and diseases because differential susceptibility in the parents may lead to asynchronous flowering (Murty et al. 1994).

Pearl Millet

An Overview of Pearl Millet Cultivar Development and Maintenance

C T Hash

Pearl millet (*Pennisetum glaucum* (L.) R. Br.) is the staple cereal grown in the hottest and driest areas of the world for forage, grain, and stover. Since it is a cross-pollinated crop in which commercially exploitable cytoplasmic nuclear male-sterility systems are available, both open-pollinated cultivars (synthetics and composites, collectively referred to as "varieties") and hybrid cultivars (single-cross, three-way, and topcross hybrids) are practical. This section will cover breeding, maintenance, and seed multiplication procedures applicable to both groups of cultivars.

Breeding Objectives

Pearl millet is a major food and feed crop of subsistence farmers in hot and dry environments throughout the semi-arid tropics. Yields are low and unreliable—but higher and more reliable than any other available alternative crop grown in these regions. Breeding objectives for a staple cereal in such environments would be very different from those for irrigated crops, e.g., rice or wheat. Farmers require a reliable source of grain for food, and stover for construction material, fuel, and/or livestock feed. They require cultivars that produce enough surplus in the good years, even with little or no use of commercial inputs, to help them through the bad years. Over and above stable productivity, the cultivar must be of a quality acceptable for the purposes for which it is intended. In this scenario, the breeder needs to focus on improving yield performance on-farm as opposed to on-station. Improvement in tolerance or resistance to relevant biotic and abiotic stresses is also an important breeding objective.

The following objectives may have relevance to pearl millet improvement in different target environments.

Abiotic stresses:	Drought (escape, tolerance), heat, soil acidity, soil fertility (response to fertilizer application, and tolerance of poor fertility).
Biotic stresses:	Birds (escape, nonpreference bristles), diseases (downy mildew, ergot, pyricularia, rust, smut, viruses), insects (head miner, stem borer), *Striga*.
Yield:	Forage (potential—plant/animal product, stability), grain (potential, stability), stover.
Quality:	Forage (in vitro dry-matter digestibility, lignin (brown midrib), palatability (visual assessment), grain [feed and food (chemical, milling, organoleptic)].
Market demands:	Grain color, grain shape, grain size, stem thickness, and uniformity.
Seed:	Brightness, longevity, vigor.
Stover:	Construction material, feed, fuel.

Certification requirements: Stable male sterility of seed parent, unique trait combinations.

Factors to be considered when choosing breeding objectives are the importance of the trait, availability of genetic variability for the trait (preferably in desirable agronomic backgrounds), availability of cost-efficient screening procedures for the trait, and the time available before another cultivar release is needed.

Once these general breeding objectives are identified, it is necessary to decide upon the form of the genetic package to be delivered to farmers. Only after this decision is made is it really possible to develop reasonable work plans to do the breeding research required to deliver an adoptable cultivar to farmers.

Cultivar Types

Pearl millet cultivars are of two types: open-pollinated cultivars and hybrid cultivars. Open-pollinated cultivars differ from hybrids primarily in their ability to self-perpetuate and the degree of variability available in them. Seed harvested from an isolated plot of an open-pollinated cultivar will have essentially the same yield potential and uniformity as the crop from which it was harvested. However, in case of hybrids it is necessary to reconstitute the cultivar by crossing its parents to produce fresh seed to retain uniformity and yield potential of the hybrid cultivar.

Hybrid cultivars have several advantages to seedsmen and farmers compared to open-pollinated cultivars. They include higher yield potential within a given maturity, ability to combine desirable characters from different parents into a single cultivar, and greater uniformity (facilitating birdscaring and harvest operations). Further, closed pedigrees and the necessity of reconstituting hybrids from their parents allow private industry to protect their intellectual property resulting from their investment in research and development.

The advantages of open-pollinated varieties are of two types: (1) their ability to self-replicate (facilitating farmer-to-farmer spread), and (2) their inherent genetic variability. This variability within open-pollinated varieties contributes to stability of performance by reducing risks of crop failure due to drought, downy mildew, ergot, and smut.

Open-Pollinated Cultivars

There are three general types of open-pollinated cultivars of pearl millet:

1. Mass-selected landraces
2. Products of recurrent selection within a breeding population
   (a) Cycle bulk
   (b) Recombination of selected progenies
3. Synthetic varieties bred by random mating a set of inbred lines

Broadly, open-pollinated varieties are products of traditional crop improvement by farmers, or bred by random mating a selected fraction of a variable breeding population.

Hybrid Cultivars

Several types of hybrid cultivars are possible, depending on the genetic structure of their parental lines.

These are discussed below.

Single-cross hybrid:	Based on two uniform inbred parents (e.g., A1 x R), where A1 (male sterile) is maintained by B1 (maintainer line).
Three-way hybrid-	Based on three nonrelated uniform inbred parents [e.g., (A1 x B2) x R]; B2 is maintainer to other than A1.
Modified three-way hybrid:	Based on two related uniform inbred parents as female and a third nonrelated uniform inbred parent as male [e.g., (A1a x B1b) x R].
Topcross hybrid:	Based on a uniform inbred parent and a more variable, less inbred pollen parent (e.g., A1 x R-population).
Three-way topcross hybrid:	Hybrid based on two uniform inbred parents to produce a F_1 female parents, and a nonrelated, variable, relatively less inbred used as a male parent.

Hybrid Types Based on Seed Production Technology

Hybrid types can also be described based on seed production technology.

Chance hybrids:	Based on random crossing between several parents sown in bulk.
CMS-based hybrids:	Based on male-sterile seed parents.
Protogyny-based hybrids:	Also known as pro-hybrids, these are based on male-fertile seed parents. Seed production requires uniform flowering of uniculm female. Male parent must shed ample pollen before anthesis of female.

The open-pollinated cultivars are also referred to as varieties. These can be maintained and multiplied by random mating their representative bulk in isolation. These varieties are amenable to improvement by mass selection in the breeder seed isolation plot itself, provided the isolation is grown in the target environment (location and season).

These two types of classification of hybrid cultivars are complementary, not mutually exclusive. Thus, it is possible to have a CMS-based three-way topcross hybrid (although maintenance of all the necessary parental stocks for such a hybrid would be complicated).

Reproductive Biology of Pearl Millet

Faujdar Singh

Pearl millet belongs to the family Poaceae, subfamily Panicoideae, tribe Paniceae, subtribe Panicinae, genus Pennisetum, and section Penicillaria (Pernes et al. 1984). Harlan (1971) has reported that the center of origin of pearl millet is in the Sahelian zone in Africa between western Sudan and Senegal.

Pearl millet has also been described earlier as *Pennisetum typhoides* (Burm) Stapf and Hubb., and *Pennisetum americanum* (L.) Leeke. It is primarily cultivated for grain purposes in India, New Mexico, Southeast Asia, and the West, East, and Southern African countries, and in the United States of America for fodder. Pearl millet is an annual plant, which grows well on light-textured soil under low moisture conditions. This chapter deals with the pearl millet plant and its reproductive system.

Germination and Seedling Development

Pearl millet seeds germinate in 3-5 days when sown at a depth of 3-5 cm in the soil with sufficient moisture and at optimum temperature. Germination begins with the absorption of moisture by the seed due to which it swells and ruptures the seed coat. A small coleoptile and a radicle emerge from the seed (Fig. 1). The coleoptile emerges out of the ground, and the first leaf develops from its tip.

Pearson (1975) reported that final germination of pearl millet was independent of day/night temperatures when tested in a range of 15/10°C to 33/28°C. However, the rate of germination and emergence, seedling survival, leaf-area expansion, and dry-matter accumulation were highest at 33/28°C.

Root System

The pearl millet root system consists of three types of roots: primary, secondary, and brace roots (Fig. 2).

Primary roots. The radicle roots *or* seminal roots after germination develop into the primary roots. These roots continue to develop for 45-60 days.

Secondary roots. These are also known as adventitious roots. The first pair of secondary roots develops from the first node of the primary root at the two- or three-leaf stage. The next node gives rise to the second pair of secondary roots, and thereafter, four to six roots are produced at each node. These roots can penetrate up to a depth of 5 m into the soil.

Crown or brace roots. These roots develop from the lower nodes of the stem at or above ground level. They provide anchorage to the plant.

The maximum root spread in pearl millet is confined to 25-30 cm of the soil area around the plant.

Shoot System

The pearl millet shoot consists of a stem, tillers, and leaves during the vegetative stage (Fig. 3).

Figure 1. Seedling emergence in pearl millet.
(Source: Maiti and Bidinger 1981)

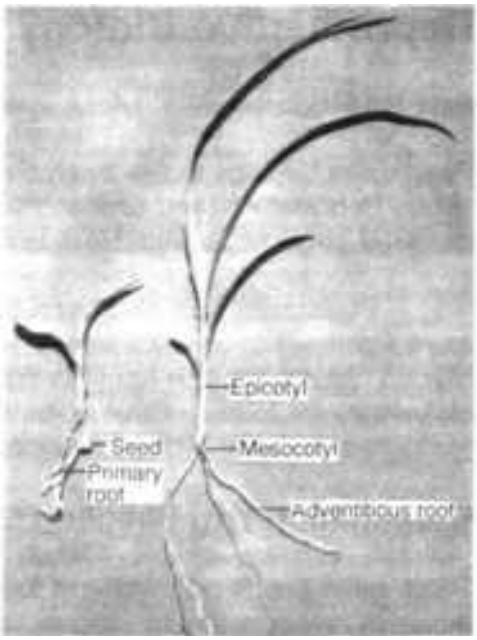
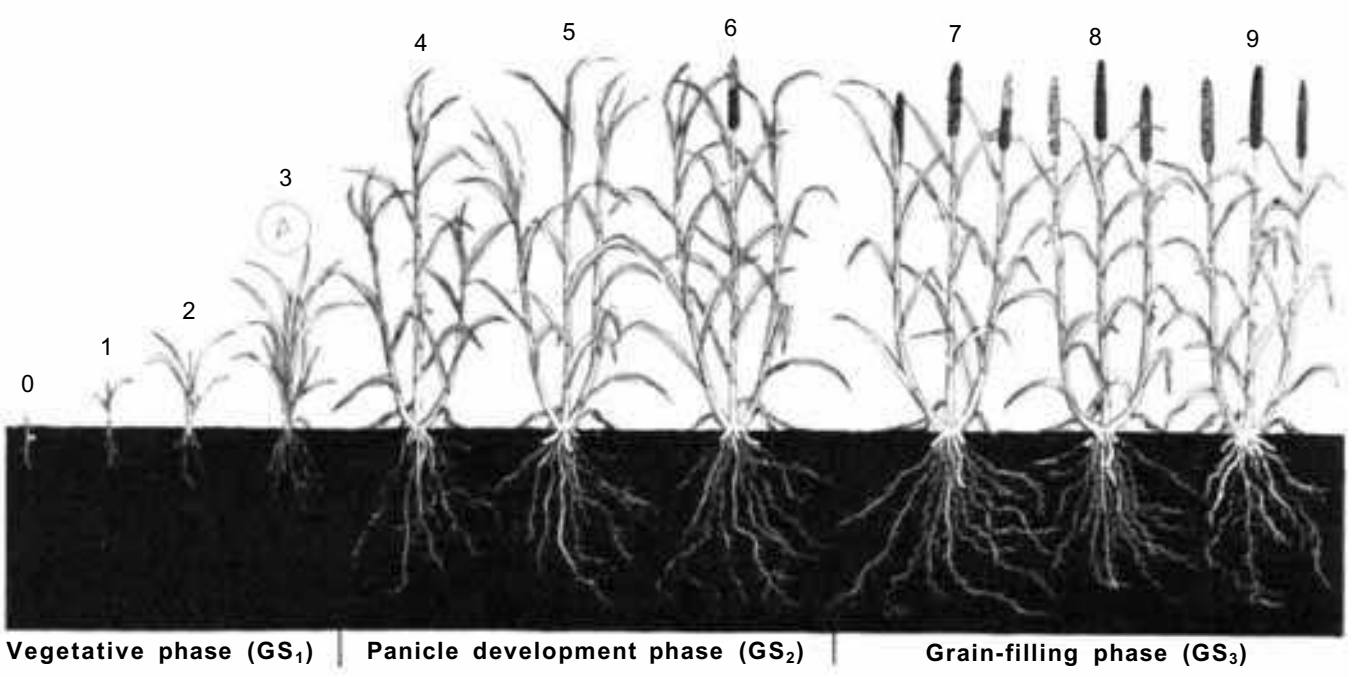


Figure 2. Parts of a pearl millet seedling.
(Source: Maiti and Bidinger 1981)



GS_1 = from seedling to panicle initiation of the main stem

GS_2 = from panicle initiation to flowering of the main stem

GS3 = from flowering to physiological maturity period of crop

Figure 3. Growth phases of pearl millet.
(Source: Maiti and Bidinger 1981)

Stem. The pearl millet stem or culm consists of nodes and internodes. The solid stem is thick at the base. The nodes are slightly swollen, and axillary buds are present in shallow grooves at the nodes. The nodes are hairy as well as glabrous with a gradual increase in hairiness from the base to the apex. The lower internodes are largely covered by the sheaths of the leaves, while the upper internodes are only partly covered. The upper internodes are more elongated than the lower ones. The height of the stem ranges from 0.5 m to 3.0 m.

Tillers. The development of tillers starts from the lower nodes of the stem 3-5 weeks after emergence. These are called primary tillers. The secondary (axillary) tillers develop from the axillary buds at the upper nodes, usually after completion of flowering on the main stem.

Leaves. The leaves are arranged alternately in two vertical rows on the culm. They are linear in shape comprising of a leaf sheath and a blade. The leaf sheaths are light green or purple and envelop the stem slightly above the nodes. The leaf sheaths overlap at the base of the stem but are open in the upper portion. The leaf sheath is glabrous and grooved. Ligules are present at the junction of the leaf blade and the leaf sheath. They are membranous, hairy, 4-5 mm long, and clasp the stem.

The leaf blade is lanceolate, 90-100 cm long and 5-8 cm wide, with a pointed tip. The midrib is dull green. Auricles are present at the base of the leaf blade. The upper leaf surface is scarbid and hairy, while the lower one is smooth and glabrous.

The leaf area of pearl millet is calculated by measuring the length and the width (at the broadest point) as suggested by Singh et al. (1970).

Leaf area = Leaf length (cm) x Leaf width (cm) x 0.7236

Reproductive System

The shoot apex is transformed into a reproductive apex (Fig. 4) with the formation of the panicle meristem. The panicle meristem is bulbous, with a constriction at its base. It develops tunica and corpus layers in the inflorescence axis. These cells (tunica and corpus) are eumeristematic. The different floral organs develop from the apex. The organogenesis and maturation of organs in the spikelet apex are acropetal (Gill 1991).

Inflorescence. The pearl millet inflorescence is a false spike, ranging from 5 to 150 cm in length and 1 to 5 cm in diameter. The panicle is terminal, varying in shape from cylindrical to candle-shaped. The spike consists of a central rachis which is closely packed with fascicles. Each fascicle consists of one or more spikelets and a whorl of 70-80 bristles. The tip of the spike has only a single spikelet. The bristles may be free or united to form an involucre. About 10-15 bristles in the upper whorls are longer than those in the lower ones. The bristles are broader at the base and narrower at the tip. They are scarbid and green or purple. An inflorescence may contain 870-3000 spikelets with an average of 1600 (Khairwal et al. 1990).

Spikelets. The spikelets are small, lanceolate, and acute. Each spikelet consists of two glumes, one outer and one inner. The outer glume is broad, short, membranous, and truncate. The inner glume is broad and half the size of the spikelet. Between the two glumes, there are (two) florets. The lower floret is staminate and the upper floret is hermaphrodite (Fig. 5). Spikelets are generally bifloret but can sometimes be trifloret or tetrafloret; in rare instances, more than four florets are present (Maiti and Bisen 1979).

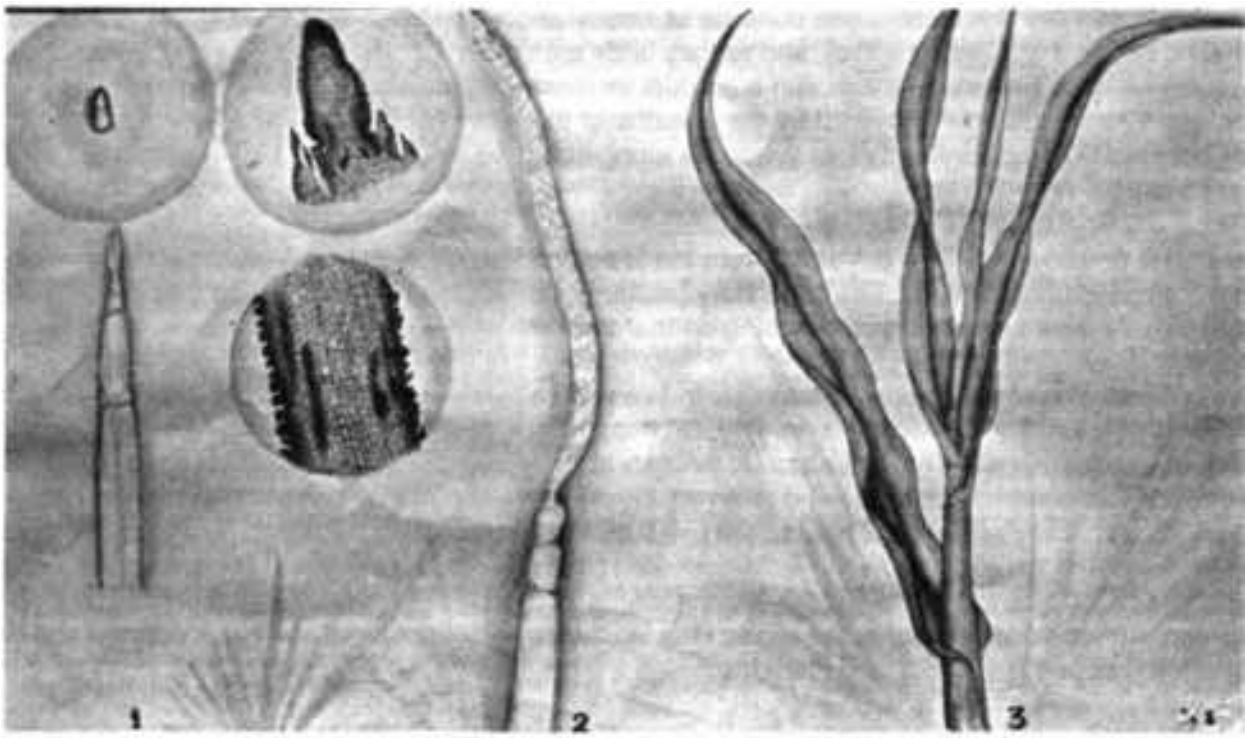


Figure 4. Primordial initiation (1), panicle development (2), and preboot stage (3) in pearl millet.

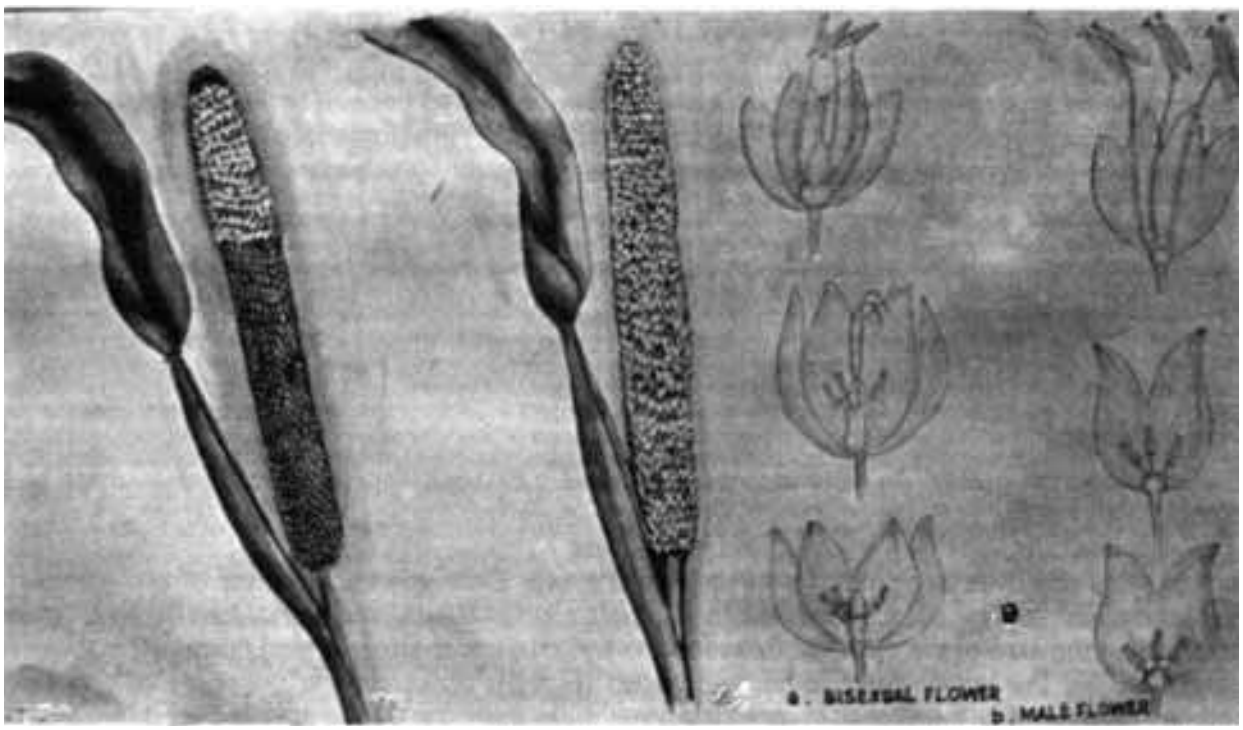


Figure 5. Seed development, bisexual, and male flowers in pearl millet.

The staminate flower has one lemma and one palea, and enclosed between them is the androecium with three stamens. The upper hermaphrodite floret has a broad, pointed lemma and a thin, oval palea, and the androecium and gynoecium are enclosed between them.

Androecium. The pearl millet androecium consists of three anthers (Fig. 5), each attached to a long filament. There is a two-layered epidermis, a tapetum, and pollen grains. The anthers are yellow or purple with a tuft of fine hairs at the apex.

Gynoecium. The gynoecium consists of a monocarpellary and superior ovary with two styles and a feathery stigma. The pistil in its young stage shows two carpels, one larger than the other. The larger one contains the primordium of the ovule. The growth of the two carpels is unequal. The thicker one, bearing the primordium, grows in girth, while the thinner one grows in length and soon overtakes the other to form the style and stigma at the top. The mature ovary has an anatropous ovule. The inner integument completely covers the ovule and forms the micropyle, and the other stops its growth at a very early stage. Thus the embryo has a scutellum, plumule, coleoptile, primary axis, coleorhiza, and radicle (Rachie and Majumdar 1980). The styles are connate at the base, bearing the stigma at the tip.

Panicle Emergence

The emergence of the panicle from the sheath takes about 4-6 days (Bhatnagar and Kumar 1960). Flowering starts after the emergence of the panicle out of the boot (Fig. 6), but in some genotypes style exertion commences before completion of panicle emergence. Stylar exertion begins first in the florets in the central upper portion of the panicle and then progresses upward as well as downward. The maximum exertion of styles is on the third day of flowering.

The flowering of pearl millet is protogynous, i.e., the stigma emerges earlier than the anthers (Fig. 7). The stigma remains receptive for 12-16 h. Protogyny is expressed in varying degrees in pearl millet, depending on the genotype and the environment (Rachie and Majmudar 1980).

Anthesis and Pollination

Anther emergence begins one day after the emergence of the stigmas is completed on the panicle. It first starts in the hermaphrodite florets followed by the staminate florets. Anther emergence is facilitated by the protogynous styles and the tufts of hair on the tips of the anthers. Anthesis continues throughout the day. The maximum anthesis is between 2000 and 0200 (Sundararaj and Thulasidas 1980).

Exertion and emergence of anthers takes about 60 min if it happens during the day; during the night it may take twice as much time or more.

Anther emergence starts in the upper portion (at about the two-thirds point) of the panicle and proceeds in both directions. The first flush of anthesis is completed in a week's time under irrigated conditions. Panicles emerging from the tillers start flowering later and the process may continue up to three weeks. In rainfed conditions, first-flush anthesis of a plant may take place over 12 days, and it may continue on the tillers till seed formation (Chalam and Venkateswarlu 1965).

The pollen remain viable for 5 h at room temperature. Burton (1965) noted that when the pollen were stored in glassine bags at 27°C, they remained 59% as effective as fresh pollen after 1 day, 10% as effective after 2 days, and only 3% as effective after 3 days. However, when stored at low temperature (4 or 5°C), they remained viable for 3 weeks (Cooper and Burton 1965). Hanna and Young (1974)

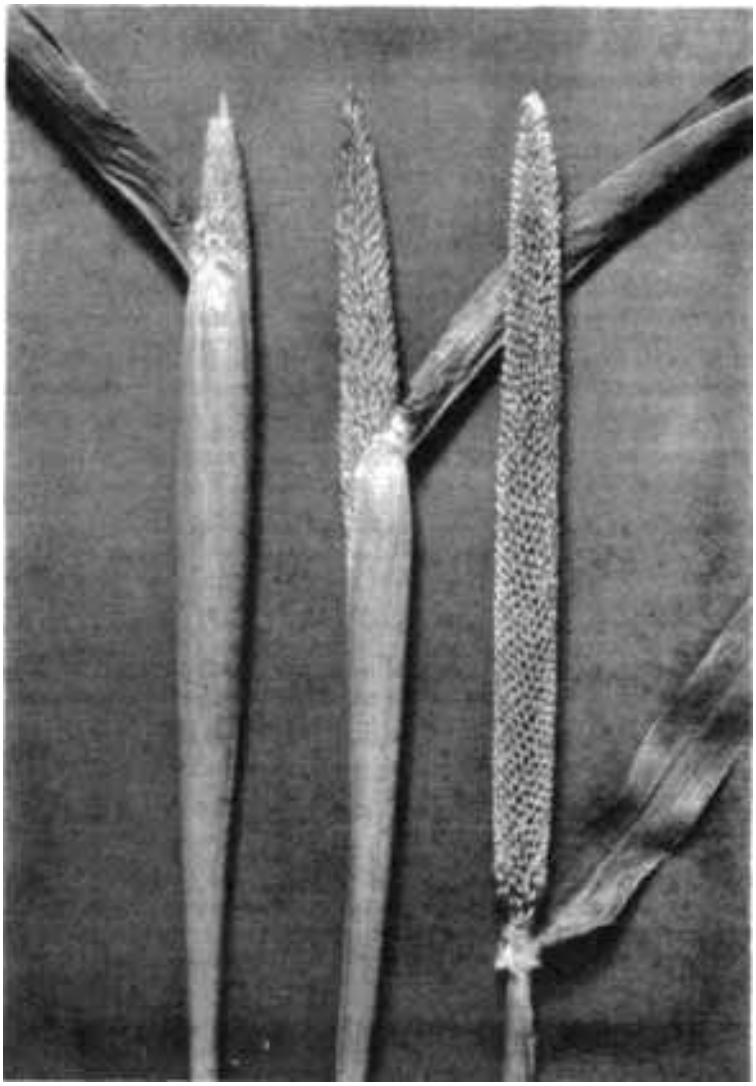


Figure 6. Pearl millet boot stage and panicle emergence stages.

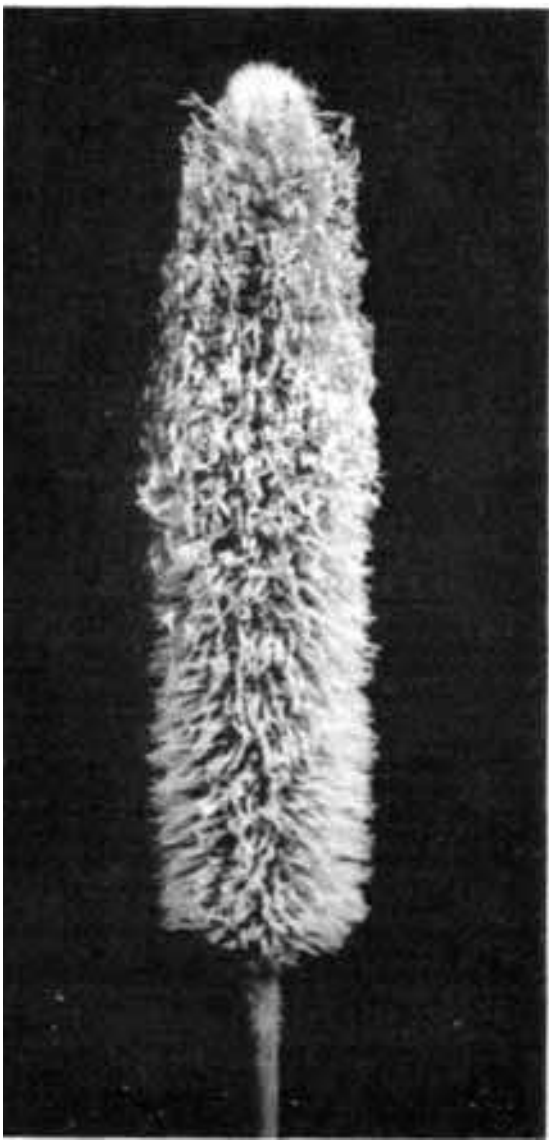


Figure 7. Protogynous stage in selfed panicle.

suggested that pollen with a moisture level of 7.5% can be stored in a plastic zip lock bag tor 185 days at -73°C, remaining 100% viable.

Fertilization and Grain Formation

After pollination, the stigmas dry up in 24 h. Seed-set can be seen in the panicle about a week after fertilization (Burton and Powell 1968). There is a gradual increase in the dry mass of grains from the milk to dough stage, reaching maximum at maturity. Physiological maturity of the grain is indicated by the appearance of a black layer just above the hylar region on the abgerminal side of the grain opposite the embryo (Fussel and Pearson 1978). At physiological maturity, the seed contains 30% moisture.

There are large variations in seed shape (Fig. 8) — obovate, oblanceolate, cuneiform, pyriform, pyramidal, elliptical, hexagonal or globular — size, and color. The grain mass varies from 3 to 5 g $1000'^{1}$ seeds for small-seeded genotypes and 10 to 12 g 1000^{-1} seeds for bold-seeded genotypes. The seeds are yellow, white, light brown or gray.

Grain Structure

The pearl millet grain is a caryopsis with three main parts: pericarp, endosperm, and germ (Fig. 9). The pericarp contains three layers of tissues: epicarp, mesocarp, and endocarp. The term bran refers to the pericarp, the seed coat, and the aleurone layer of the seed. The endosperm contains simple starch granules and protein bodies. The germ contains about 25% lipids, 20% protein, and phytin, vitamins, and enzymes. The germ of pearl millet constitutes about 17% of the total seed mass (Rooney and McDonough 1987).

Factors Influencing Flowering and Seed Formation

Photoperiod and temperature affect flowering in pearl millet. Some genotypes fail to flower when the day length exceeds 12 h. Many genotypes flower under long day length conditions (16 h photoperiod), but flowering takes place earlier under short-day conditions (Burton 1965).

Increasing the temperature up to 32°C and providing an appropriate photoperiod reduces the number of days from sowing to flowering (Hellmars and Burton 1972).

Drought may hasten flowering in some genotypes but delay it in others. A combination of high temperature and drought affect pollen viability, stigma receptivity, and seed-setting.

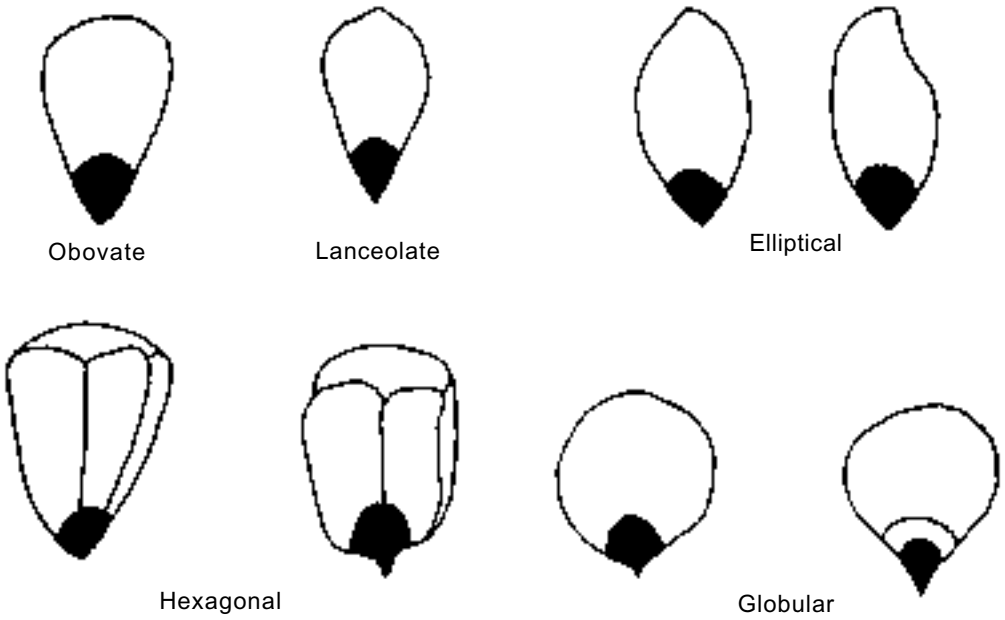


Figure 8. Grain shapes in pearl millet.
(Source: Descriptors for pearl millet)

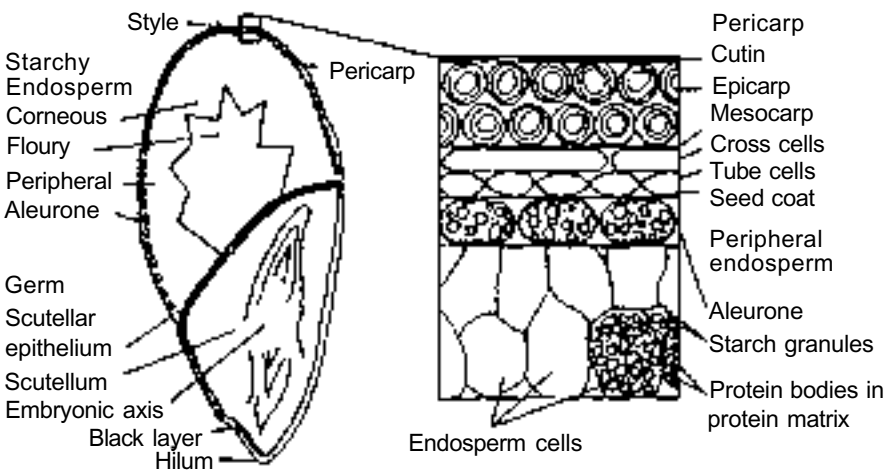


Figure 9. Pearl millet grain structure.
(Source: Rooney and McDonough 1987)

Selling and Crossing Techniques in Pearl Millet

K N Rai

The protogynous flowering behavior of pearl millet makes it a highly cross-pollinated crop. Emergence of stigmas 2-3 days before anther emergence makes crossing possible without having to resort to emasculation. At the same time, the presence of hermaphrodite flowers and stigma receptivity lasting 3-4 days make selfing also easy. However, if a pearl millet panicle is not protected from outside pollen, more than 90% of its seed are likely to be the products of cross-pollination. Selfing is done for producing the seed of F_2 populations, S_1/S_2 progenies, and inbred lines. Crossing is done for producing the seed of F_1 hybrids, full-sib/half-sib progenies, and open-pollinated varieties in a breeding nursery. Although both selfing and crossing in pearl millet require ordinary skills, careful planning is essential to ensure that the intended quantity of seed is produced and quality is maintained.

Selfing Plan

The most critical part of a selfing program in pearl millet is to plan in advance for the requirement of selfing bags as any panicle not bagged before stigma emergence will be contaminated with outside pollen and lose its identity. Thus, selfing bags should be procured and kept in reserve one season (preferably two) before the scheduled selfing season. At ICRISAT Asia Center (IAC), two types of selfing bags, white parchment paper bags and brown kraft paper bags, are used. The choice of bags depends on the cost and weather considerations. For instance, kraft paper bags of 8 cm x 36 cm size made in India cost the equivalent of US $ 3.6 per 1000 bags. The cost of parchment paper bags of the same size made in the UK is US $ 21.8 per 1000 bags. In the dry season, kraft paper bags can be used reliably and cost-efficiently. In the rainy season, however, they are not suitable as they absorb more water, take longer to dry, and hence are likely to fall apart, leading to contamination. At IAC, we use parchment paper selfing bags of three standard sizes— 8 cm x 36 cm, 8 cm x 46 cm, and 9 cm x 51 cm —depending on the size of the panicles to be selfed. For most purposes, the ideal size is 8 cm x 36 cm.

The best plant stage for selfing (bagging) is before stigma emergence. This is generally when about one-third of the panicle has emerged out of the boot. In some genotypes, by this stage of panicle emergence, stigma emergence can already have occurred. Care should be taken to bag such genotypes as soon as the tip of the panicle is visible out of the boot. The bagged panicles are stapled or clipped in the peduncle region. With experience, one would be able to know how much of the glued end of the bag should remain above the tip of the panicle to ensure that the emerging panicle does not pierce through the bag and create an opening for outside pollen to contaminate it.

Generally, it is not necessary to have a selfing symbol on the selfing bag: a panicle under a nonmarked bag is considered as selfed. Selection for good selfed seed-set is one of the selection criteria in the inbred line development of pearl millet. Thus, considering that the selfed seed-set is good, selfing of one panicle per plant will usually provide enough seed for use in pedigree breeding, provided that the panicle is >10 cm long. Selfing of 6-8 panicles of an F_1 hybrid can be expected to provide enough seed to grow an F_2 population of 1000-2000 plants and still leave enough seed for replanting, if required.

Crossing Plan

For crossing purposes, white parchment paper bags are most convenient. These bags allow easy detection of panicles that are ready to be used as males and females without having to remove the bags.

The bagging procedure is the same as in selfing, except that the bags should be clipped, not stapled. It is essential to choose the full-stigma-emergence stage of a bagged panicle to be used as a female. This ensures that once such panicles are crossed, no new stigmas will emerge later that may get self-pollinated.

Forenoon is the best time for crossing, for two reasons: (1) the dew-soaked bags become more transparent and hence allow easy detection of the right panicle stage for use as females (whitish stigmas) and males (yellowish pollen accumulated at the base of the panicles); and (2) the pollen viability is high at this time of the day, especially before 1100 h. However, experience shows that if the maximum day temperature does not exceed 38°C, crossing can be done in the afternoon as well, although it results in a small reduction in seed-set.

The amount of pollen required to be collected for crossing depends on the number of female panicles available. Thus, the first task in a crossing operation is to find out the number of female panicles with fully emerged stigmas. This is most convenient to detect in dew-soaked panicles, usually before 0900 h when the parchment paper bags are most transparent. This can usually be accomplished without removing the bags. However, after a panicle has been tentatively identified as ready to be used as a female, its flowering stage must be confirmed by quickly pushing up the bag, observing the entire panicle for full stigma emergence for no more than a second, and covering the panicle again. Once a female panicle has been selected, the clip should be placed on the glued upper end of the bag to distinguish it from others for use in cross-pollination.

As the dew dries up, the situation improves for pollen collection. Accumulation of pollen (yellowish powder) at the base of the bagged panicles indicates that they are ready for pollen collection. First, the bag is held tightly above the point of pollen accumulation, and the clip is removed to release the accumulated pollen at the base. Then, by still holding the bag tightly, the panicle is tapped with the other hand, causing the shedding and accumulation of fresh pollen at the base. This pollen is made to slip towards the glued end of the bag by bending the panicle and peduncle downwards. Thereafter, the panicle is rebagged with the same or another selfing bag if more pollen needs to be collected from it on the following day or if the selfed seed needs to be harvested from it to maintain the line. Where selfed seed is not required from the bagged panicles, these can be bagged at the beginning of anthesis, a day prior to pollen collection. These bags should not be clipped, to distinguish them from those that have been clipped for production of selfed seed. Pollen from several bagged panicles of an entry may be collected in one bag, which shall bear the plot or entry number.

The pollen collected is dusted onto the female panicles after quickly removing the selfing bags from the latter. Once crossing is completed, the bags are marked with (x) plot or entry number of the pollen parent (Table 1), and placed back over the crossed panicle and stapled. This completes the crossing procedure.

Occasionally, a portion of the panicle (usually the lower one) may not be fully pollinated due to insufficient pollen or the stigmas in this portion might not have fully emerged, giving scope for self-pollination at the later stage of flowering. Spikelets from such portions of panicles should be removed before rebagging the crossed panicles. If bulk pollen of the same line or population has been used for crossing to produce the seed, then a simple (#) mark on the crossed female panicle will be sufficient (Table 1). If one plant is crossed with another plant, as in the case of full-sibs, then the plants used as males as well as those used as females should be numbered, and these numbers should be recorded on the crossed female panicle (e.g., P 5 x P 107).

In a selfing program, it is possible to do a quick visual assessment of the approximate number of selfed panicles to determine if the program is on target. This is difficult to do when crossed seed is to be produced, especially when the same line is used as a female for crossing with a number of male lines. The same thing applies when a large number of crosses are to be made within a population to produce full-sibs or half-sibs. In such situations, maintaining a crossing record becomes necessary. This record is essentially a list of the female plots against which are written all the male plots with which they should be crossed (Fig. 1). During the crossing program, the number of panicles crossed of each combination should be recorded in the appropriate column to monitor the progress of crossing and achievement of the target. This helps ensure that only the required crosses are made.

Harvesting of Selfed/Crossed Panicles

Selfed/crossed panicles can be harvested at physiological maturity after the formation of the black layer. It is, however, advisable to harvest when the seeds are dry as this necessitates little postharvest drying. Some degree of postharvest drying is unavoidable to ensure that even late-maturing panicles, which might not have dried at harvest time, become dry for threshing. Wherever possible, about a week before harvesting, the upper glued ends of the bags are torn off and pushed down the selfed panicle so that it is exposed for some time to facilitate natural clearing of the sticking anthers. This permits harvesting of clean panicles, and also makes it possible to evaluate them for seed characters (including seed-set).

In the case of crossed panicles, the bags are left intact. Harvested panicles from a plot (line or population) are collected in a harvesting bag, which should bear the plot number. Both selfed and crossed panicles harvested from a plot can be collected in the same bag, which should be stapled.

Threshing and Storage

After drying, selfed panicles are separated from the crossed panicles and threshed individually (in pedigree selection) or as a bulk (in bulk pedigree selection). The crossed panicles of a plot are threshed as a bulk if they were all crossed with only one male parent. They need sorting out if they were crossed with more than one male parent. These panicles are threshed by hand or by a machine. The seeds are then cleaned of glumes in a tray and transferred to seed packets, bearing the plot number for seeds from selfed panicles and "plot x plot" number for seeds from crossed panicles. Pieces of naphthalene balls are put in the seed packets to avoid damage from pests. These seeds can be stored at room temperature for a year without any serious loss of viability.

Table 1. An illustration of the symbols used for various types of crosses in pearl millet.

Cross type	Symbols
Line x line	81 B x J 104 (for entries) 206 x 701 (for plots)
Plant x population	P... x EBC (different populations) # (same population)
Line x population	81 B x EBC (entry x population) 206 x EBC (plot x population)
Population x population	NC x EBC (for entries) 805 x 920 (for plots)
Plant x plant	P 5 x P 107 (same population) NC (P 5) x EBC (P 210) (different populations)

	Number of crossed panicles					
Female plot (number)	Male plot (number)					
	86	180	210	275	380	400
5	i	ii	iii	ii	iiii	iiii
17	iiii	ii		ii		
210			i			
285					iiii	
362		iiii				
390	iiii	iiii	iiii	iiii	iiii	iiii
451		iii		iiii		
480	iiii	iiii	iiii	iiii	iiii	iiii

Figure 1. Recording progress in crossing work with a target of four crossed panicles per combination.

Development, Production, and Maintenance of Male-Sterile Lines in Pearl Millet

K N Rai

The widespread cultivation of single-cross hybrids of pearl millet in India reflects the great success of cultivar development and seed production technology. These hybrids are produced by crossing restorer lines onto cytoplasmic-genic male-sterile lines, also called cytoplasmic male-sterile (CMS) lines. The CMS system theoretically provides a mechanism to produce pure single-cross hybrid seed on a commercial scale (under open pollination in isolation). In practice, however, several genetic and nongenetic factors determine the success of this system. The two most important genetic factors are: (1) the stability of male sterility under various environmental conditions, and (2) the availability of marker(s) for the detection of off-types. The nongenetic factors are various aspects of seed production and seed maintenance, including purification of seed stock. Besides the question of the genetic purity of hybrid seeds, there is, of course, the related question of the economic feasibility of hybrid seed production.

This paper provides a brief description of the nature and sources of CMS and development of male-sterile lines, and a somewhat detailed account of production and maintenance of nucleus/breeder seed of male-sterile lines and their respective maintainer lines.

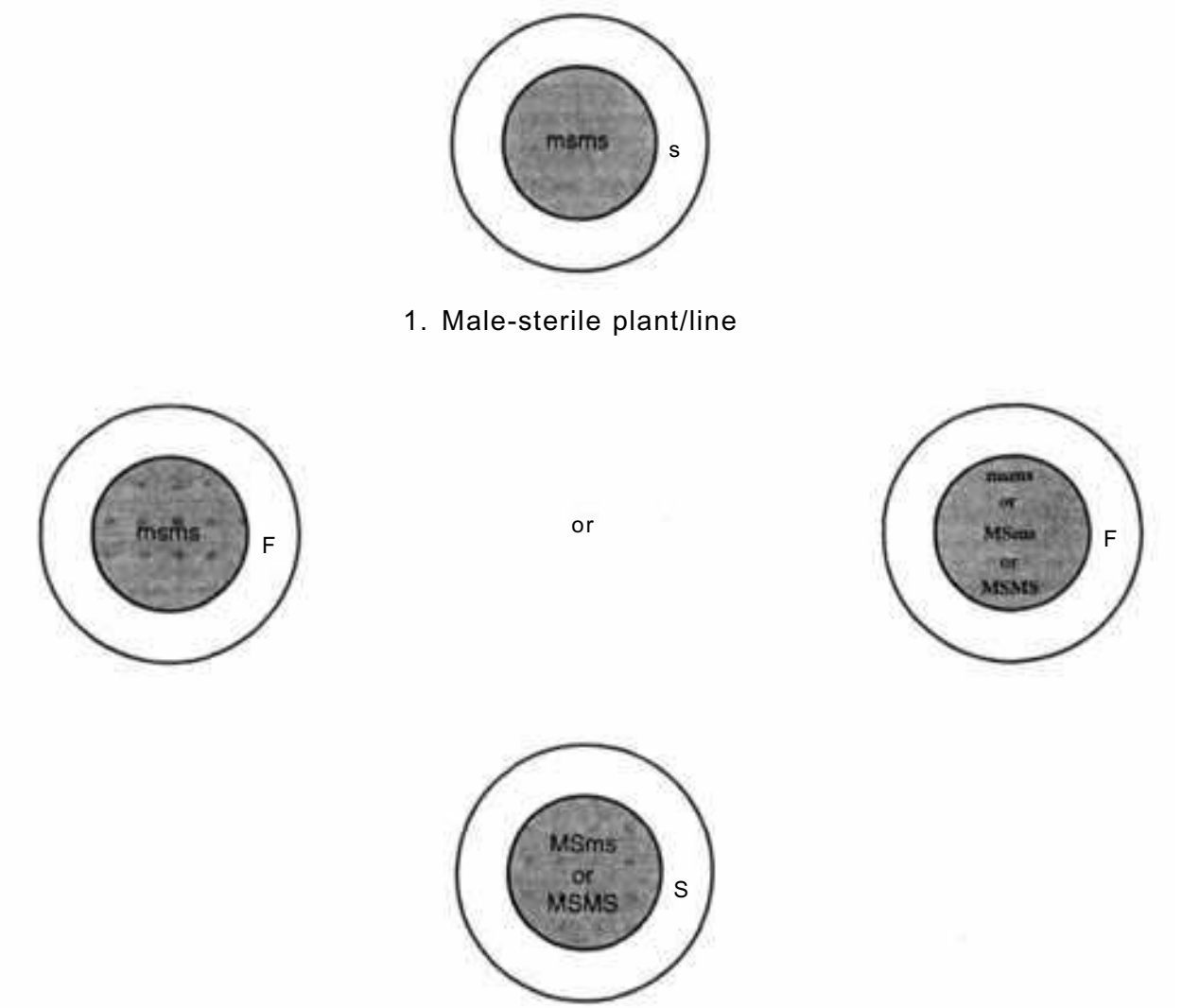
Cytoplasmic-Genic Male Sterility

Cytoplasmic-genic male sterility results from an interaction between cytoplasmic factors and nuclear genes (Fig. 1). It is now known that male-sterility-inducing cytoplasmic factors are mitochondrial genes; hence it would be more appropriate to call this type of male sterility cytoplasmic-nuclear male sterility (Hanna 1989).

Identification of CMS. Male-sterile plants are easily identifiable at the time of anthesis by their shrivelled anthers, which do not shed pollen. The sterility could be due to genetic factor(s) in the nucleus alone, in which case it is called genetic male sterility (GMS). When GMS plants are crossed with a wide range of inbreds, they never produce hybrids in which all or most of the plants are male sterile. In contrast, when CMS plants are crossed with a set of such inbreds, they produce some hybrids in which all or most of the plants are male sterile. This is the sole criterion to distinguish CMS from GMS.

CMS sources. Several well-classified CMS sources are available in pearl millet. These are called A_1, A_2, A_3 (Burton and Athwal 1967), and A_4 (Hanna 1989). Besides these, there are others that have not yet been classified well (Rai and Singh 1987). At present, however, only the A, system is under commercial utilization. There are three main reasons for it: (1) the male sterility of this system is more stable than others except A_4; (2) several inbred lines identified as restorers of the A, source produce sterile hybrids on the A_4 source and hence are unsuitable for the production of grain hybrids on the A_4 source; and (3) most of the breeders are presently contented with the male-sterile lines based on the A, source.

Genetics of CMS. An oversimplified model assumes that the cytoplasmic factor interacts with a single recessive nuclear gene in the homozygous (ms_1ms_1) condition (Fig. 1) to produce the A, type of male sterility (Burton and Athwal 1967). There are indications, however, that more than one major gene might be involved (Siebert 1982) and in fact, some modifiers might be involved as well (Rai and Singh 1987; Rai and Hash 1990).



S =Sterile cytoplasm, F=Fertile cytoplasm;
MS=Dominant nuclear gene for male fertility;
ms=Recessive nuclear gene for male sterility.

Figure 1. Interaction between cytoplasm and nuclear genes causing male sterility in pearl millet.

The nuclear genes that interact with the cytoplasmic factors to produce male sterility in the A_2, and A_3 cytoplasms are suggested to be different from that of the A, cytoplasm (Burton and Athwal 1967). The genetics of the other CMS systems has not yet been investigated.

Development of Male-Sterile Lines (A-lines)

The first step in the development of an A-line is to breed a good maintainer line (B-line). Once this has been achieved, an A-line is developed simply by backcross transfer of the nuclear genome of the B-line into the sterility-inducing cytoplasm of an A-line.

Maintainer line (B-line). A maintainer line is an inbred line that produces a sterile hybrid when crossed on a male-sterile line (A-line). Thus, B-lines are simply identified by crossing them on an A-line and identifying sterile hybrids. New A-lines are developed by backcrossing these B-lines into the cytoplasm of an A-line.

However, just because an inbred line has proved to be a B-line, it does not become a candidate entry for conversion into a commercially viable A-line. The B-line should have several traits to make it worthy of conversion into an A-line. Some of the essential traits include: high seed yield, good lodging resistance, good pollen production and stigma receptivity, maturity appropriate to the target environment, resistance to pests and diseases (e.g., downy mildew), and good combining ability. Some of the desirable traits include: short to medium plant height, synchronous tillering, medium to large seed size, grain color as per consumers' preference, and morphological marker(s). Once the requirement of all the essential traits is satisfied, and some or many of the desirable traits are also present in a B-line, it makes a good candidate entry for conversion into an A-line.

Conversion of a B-line into an A-line. A highly inbred B-line, when crossed onto an A-line, will produce an F_1 hybrid in which all the plants will be fully male sterile. The backcrossing of this sterile F_1 to the B-line will produce a BC_1 progeny in which all the plants will again be fully male sterile. In such a situation, the subsequent backcrosses will produce advanced BC progenies which will carry only male-sterile plants. If the B-line is highly uniform for all morphological traits, bulk pollen can be used from the B-line during the backcrossing program (Fig. 2).

If the B-line is variable for a trait (including genetic variation for sterility-maintenance ability), selection of individual plants for (Plant x Plant) crossing during the backcross program is resorted to (Fig. 3). Generally 3-5 plants from each of the B-lines and the corresponding BC progeny are adequate. This requires sowing of each selfed progeny of the B-line and its corresponding BC progeny in paired plots, each in a single row of 2 m, consisting of 15-20 plants. At each BC generation, selection is made both between-and within-the BC progeny rows as well as between-and within-the B-line rows to ensure that the numbers do not explode and that the B-line is further improved.

Production and Maintenance of Nucleus Breeder Seed

An efficient nucleus/breeder-seed production technology has four major components:

- maximization of seed yield per unit area;
- reduction of seed cost;
- timely availability of seed; and

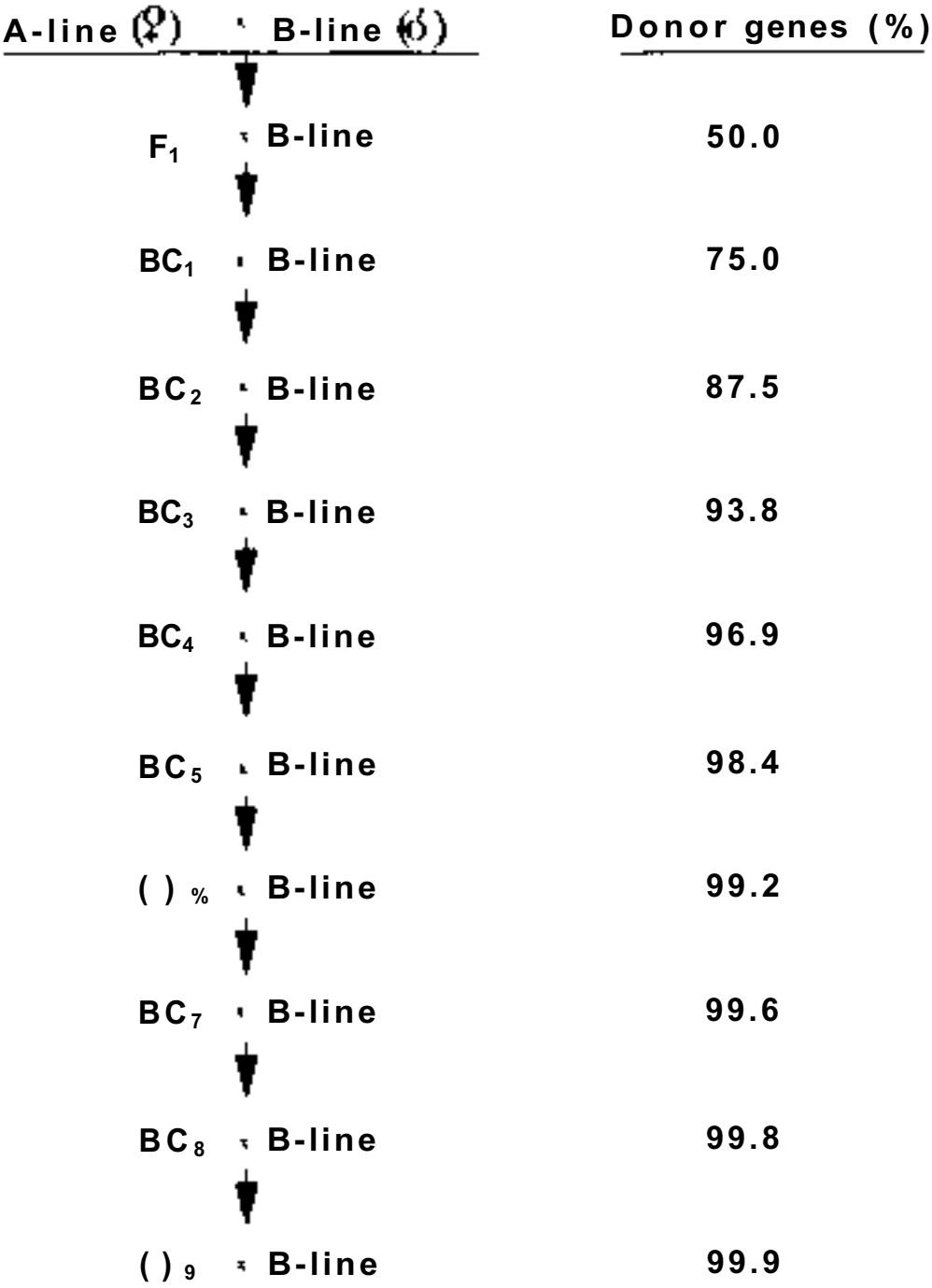
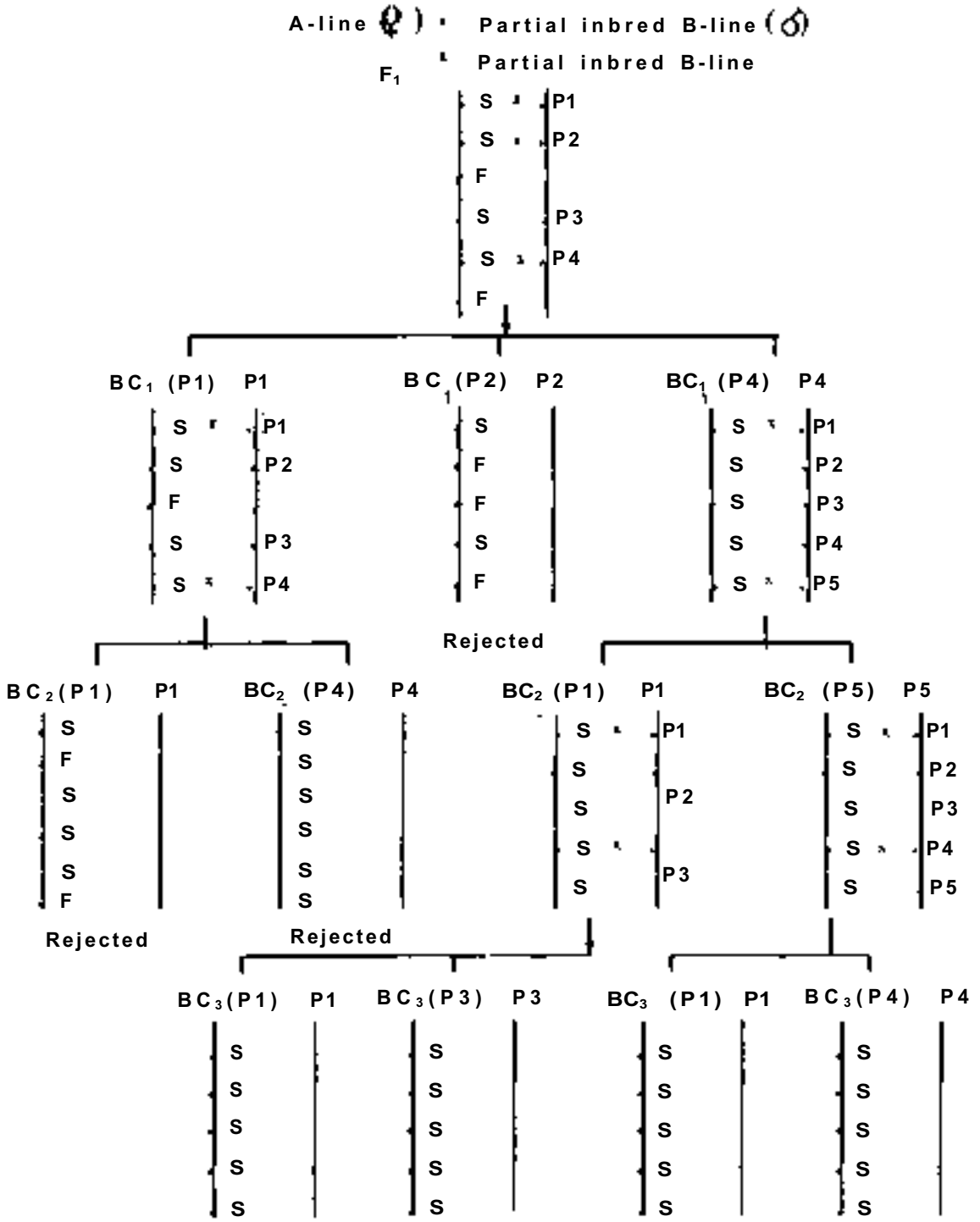


Figure 2. Conversion of a highly inbred B-line into an A-line.



- Proceed further with any selected pair.
- Drop P x P crossing program
- Resort to L x L crossing/backcrossing

(S = Sterile; F = Fertile)

Figure 3. Conversion of a partial inbred B-line into an A-line.

- highest quality of seed in terms of genetic purity, seed vigor, and germinability, free of unwanted materials.

These objectives can be achieved by observing the following practices.

Site selection. Pearl millet is highly sensitive to waterlogging. Therefore, seed production of this crop requires well-levelled land with good drainage. Improved genotypes of pearl millet have been shown to respond to applied nitrogen levels of up to 100 kg ha^{-1}. Thus, selecting a fertile field or growing the seed crop under high levels of applied fertilizer is recommended. However, growing the seed crop on deep soils should be avoided, particularly in the rainy season. The field should have access to irrigation facilities even in the rainy season, and should not have been sown with pearl millet in the preceding season.

Selection of season. Pearl millet is basically a rainy-season crop. It can, however, be successfully grown in the dry season with irrigation, provided the minimum temperature does not fall below 12°C and the maximum temperature does not exceed 38°C. In fact, higher grain yields have been reported from dry-season crops than from rainy-season crops in India. This is due to longer sunshine hours, less lodging, less risk of pollen wash and hence better seed-set, better uptake of nutrients due to good moisture control through irrigation, and fewer disease and insect pest problems. Moreover, dry-season crops produce better quality seed that is disease-free and has an attractive lustre.

It is advisable, wherever possible, to produce both nucleus and breeder seed in the dry season because being the off-season, there is greater likelihood of getting good isolation. The rain-free period in this season facilitates much better control over roguing operations. Both good isolation distance and roguing are essential to maintain the genetic purity of male-sterile lines. Also, the longevity of seeds produced in the dry season is better than those produced in the rainy season.

Isolation distance. The protogynous flowering behavior of pearl millet puts it at a greater risk of contamination from windborne alien pollen than maize and sorghum. Experimental data for determining the isolation distance for seed production plots of pearl millet continue to be a major concern (Chopra 1982). For pearl millet, the distance between the seed production plot of the intended genotype and those of others has been arbitrarily fixed; it varies greatly for various seed classes. The isolation distance recommended for nucleus-seed production plots is at least 2 km, and for breeder-seed production plots it is more than 1 km (Andrews and Harinarayana 1984). Seeds of A- and B-lines can be produced in the same seed production plot, provided utmost care is taken in harvesting these lines. Alternatively, they can also be produced in different plots with an isolation distance of 5 m between the two.

Several factors need to be taken into account while fixing the isolation distance. These include wind direction and velocity, humidity, windbreaks (including the intervening fields sown with other species), and the size of the plots serving as the source of alien pollen load. Sometimes it is argued that if the seed production plot of the intended genotype is upwind, the isolation distance requirement for it may be slightly relaxed. It is, however, not always certain before sowing what the wind direction will be at the time of flowering and whether or not it will always be unidirectional.

The recommended isolation requirements given above apply not only to field sowings of other genotypes but also to volunteers, although the alien pollen load from the latter will be of much less consequence. The problem of isolation distance can be solved to a great degree by resorting to the "seed village" approach as practised in India (Chopra 1982). This approach would require all farmers of a village to produce seed of the same genotype. The "seed village" approach also makes the seed

certification exercise more convenient and less expensive.

Direct sowing vs transplanting. Direct sowing is a more widespread practice for the production of all classes of seeds. However, in certain areas, transplanting of 18-20-day-old seedlings from nurseries is preferred to direct sowing because:

- the field might be occupied by another crop at the appropriate sowing time;
- transplanting saves expenditure on weeding and irrigation water which would be incurred for the initial 18-20 days in the direct-sown crop;
- transplanting requires only about 30-40% of the seed quantity required for direct sowing;
- a transplanted crop has a much higher establishment success rate than the direct-sown crop, without any need for thinning; and
- a transplanted crop is believed to yield more than the direct-sown crop because unhealthy seedlings are discarded and there is a much better control over plant spacing.

Under both sowing methods, it is recommended to maintain an interrow spacing of 60-75 cm and an intrarow spacing of 15-20 cm in the nucleus- and breeder-seed production plots. The lower plant population attained with these spacings will allow full plant expression and facilitate easy identification of off-type plants and deviant phenotypes, and leave adequate room for undertaking intensive roguing. The wider spacing also works in favor of achieving a high seed-multiplication rate (i.e., ratio of seed sown to seed harvested).

To avoid sowing errors in the seed production of all seed classes, it is recommended that the direct sowing or transplanting of all rows of the A-line is completed before beginning the sowing or transplanting of the B-line. In case of machine sowing, both the A-line and B-line have to be and can be sown simultaneously with a negligible chance of errors.

A-line/B-line ratio. There is little literature on the optimum A-line/B-line ratio for pearl millet. Of course, much would depend on the pollen-producing ability of the B-line and the row-to-row spacing. The recommended ratio is four rows of the A-line to two rows of the B-line (Khairwal et al. 1990), but it can be six rows of the A-line to two rows of the B-line, if the latter is a prolific pollen producer. The seed-production season may also affect the optimum A-line/B-line ratio. For instance, the greater risk of pollen wash and ergot (a panicle disease) in the rainy season would be a case for a closer A-line/B-line ratio than for a dry-season crop. It is a common practice to sow 4-8 rows of the B-line on all four sides of the seed-production plot (Fig. 4). These borders serve not only as an additional source of pollen for better seed-set in the A-line rows but also as a trap for alien pollen from outside sources. For easy identification of A-line rows from B-line rows which are morphologically similar (except for the difference in pollen shedding, which is discernible only during flowering), it is advisable to maintain a record of the sowing plan of A-line and B-line rows (Fig. 4) till the end of harvesting. Alternatively, all B-line rows are marked with stakes at one or both ends, *or* live-marked with plants of other species (e.g., sunn hemp and sunflower) with some convenient spacing within the rows.

A-line/B-line synchronization. In pearl millet, A-lines flower about 2 days earlier than the corresponding B-lines. If the A-line has a longer duration of stigma receptivity (>3 days), no synchronization problem is likely to occur in the seed production of A-lines.

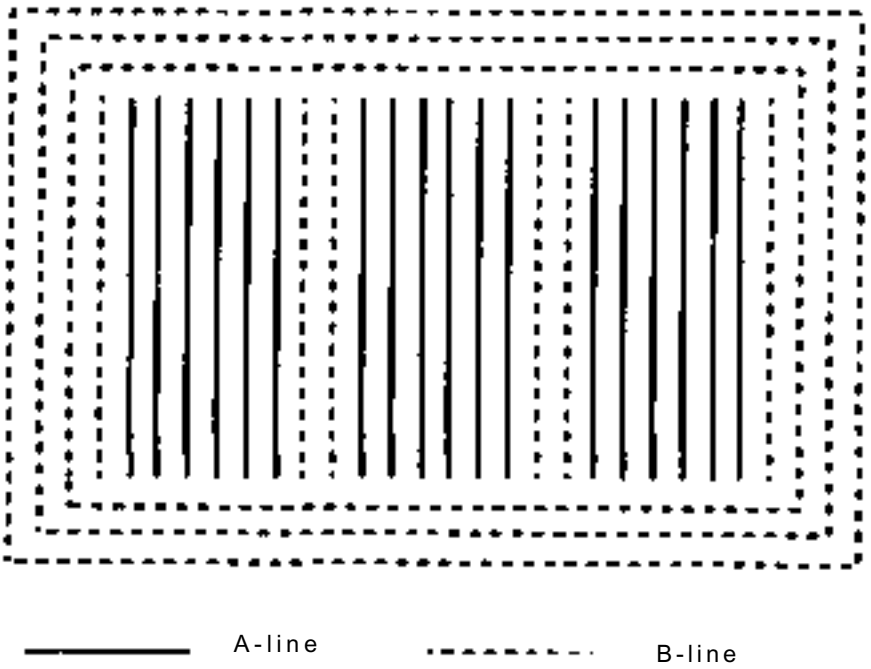


Figure 4. Sowing pattern of A- and B-lines for seed production in pearl millet.

will essentially be identical to the maintainer line, which would have no effect on the purity of the seeds harvested from the A-line, provided they are not included in the harvest. Fortunately, the majority of the pollen shedders found in pearl millet have been reported to arise from mutations in the cytoplasm (Burton 1977).

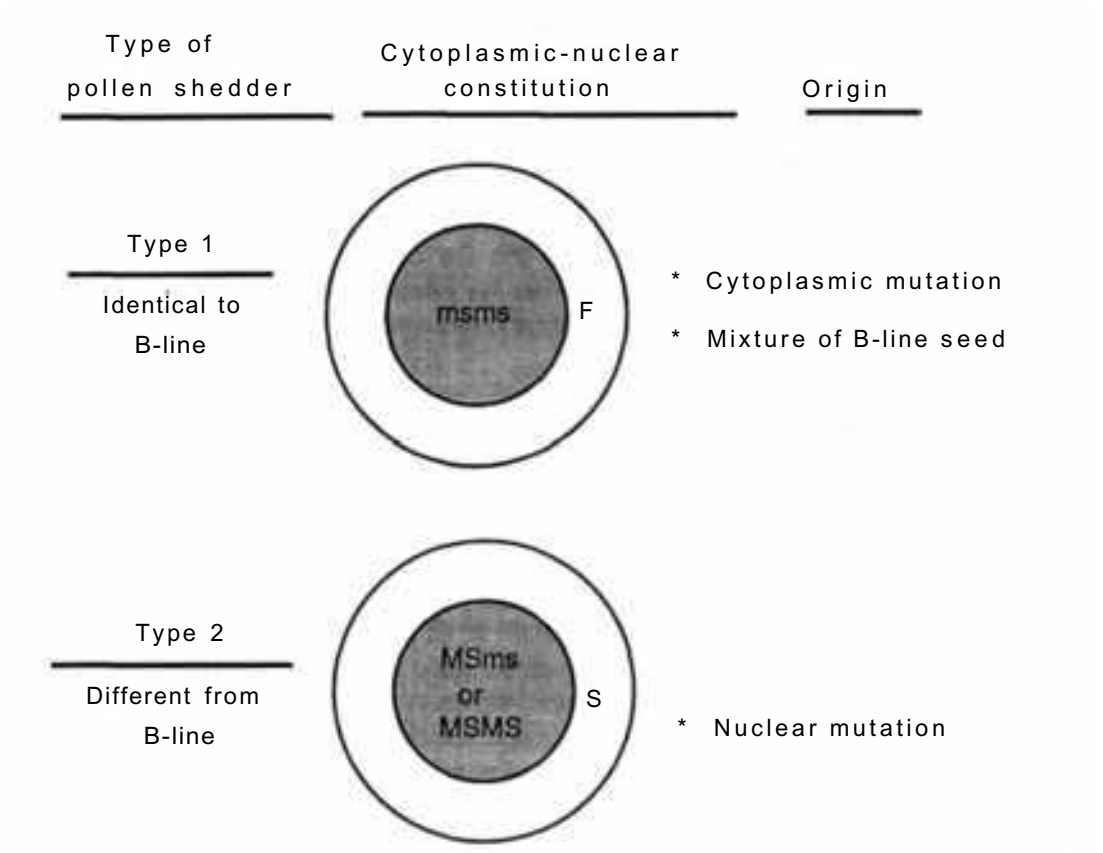


Figure 5. Origin of pollen shedders in the A-line.

Pollen shedders of nuclear origin have a different implication in maintaining the genetic purity of both the A-line and B-line. The only way to remove this type of impurity from the nucleus seed is to undertake plant x plant (P x P) crossing between the A-line and the B-line, followed by one backcrossing to the progenies of the B-line, with a view to discarding those crosses and backcrosses that are fertile, and bulk the seed of those backcross families which are uniformly sterile to reconstitute the A-line. The bulking of the corresponding B-line families would reconstitute the B-line. Our experience with two diverse male-sterile lines having a low proportion of pollen shedders indicates that the frequency of pollen shedders is higher in the rainy season than in the postrainy season. Thus, the evaluation of P x P crosses and backcrosses for fertility/sterility will be most effective in the rainy season.

Since anthesis starts in the night, morning hours are the best time for roguing pollen shedders in the A-line. Cooper and Burton (1965) have shown that when stored at 26.7°C for up to 24 hours, the loss of pollen viability in pearl millet is less than 50%. Thus, for this reason too, morning is the safest time for pearl millet field activity not only for roguing pollen shedders and off-type plants but also for avoiding

contamination of seed-production plots with pollen carried inadvertently from other breeding fields visited earlier.

In the case of nucleus- and breeder-seed production, roguing is required to be more stringent. It involves the removal of even those plants appearing to be phenotypic deviants of the target genotype. It should be noted that the highly cross-pollinated nature of pearl millet provides a potential mechanism for small changes in various plants to come together and cause, after recombination, genetic shifts in the parental lines, if the pressure of roguing at the nucleus- and breeder-seed level is relaxed.

Harvesting, threshing, and grading. The B-line should be harvested first, and the bags/heaps should be double-labelled (one label inside the bag and another outside) and stored, if possible, separately. The labels should have on them the name of the line, the field, and the crop season. The field should be checked carefully to ensure that no panicles of the B-line are left in the seed plot. After completing these practices, the harvest of the A-line can be taken up. Its panicle bags/heaps should also be double-labelled and stored separately. The panicles should be dried well down to 12% moisture before they are taken up for threshing.

Threshing and processing of the A-line and B-line seeds should be done separately. Processing includes removing seeds of other crops and weeds, and inert matter from the seed-lot; and grading it to the standard size typical of the genotype, based mainly on the seed size and shape.

Seed treatment and storage. The seeds should be treated with a mixture of fungicide and insecticide to disinfect and protect them from seedborne and soilborne pathogenic organisms and storage pests (Khairwal et al. 1990). Application of thiram 75% WDP @ 85 g for 100 kg^{-1} seed is a practice followed by the National Seeds Corporation in India. The treated seed is stored in standard containers that are sealed and labelled both inside and outside. The label inside should have on it the name of the crop, the name of the variety, the class of seed, the season, and the field/place where the seed was produced. The label outside should have additional details such as seed purity, germination percentage, etc. Sealed containers of the nucleus seed are stored at 4°C under 20% relative humidity. The breeder seed is stored at 10°C under 20% relative humidity.

Forecasting land and seed requirements. The amount of seed available in a seed class is the principal factor determining the amount of seed one can expect to produce in a subsequent seed class. Thus, an efficient seed-production technology should be able to forecast the seed and land requirements for various seed classes, and plan the seed-production program accordingly.

Based on 3 kg ha^{-1} seed rate, 6:2 ratio of A-line and B-line (R-line) rows, and seed yields of certified-, foundation-, and breeder-seed-production plots @ 800, 600, and 400 kg ha^{-1} respectively, the land and seed requirements for a target area of 100 000 ha under hybrid are given in Table 1. Even with the conservative seed yield assumed in this calculation, just 45 g of A-line seed, 15 g of B-line seed, and about 200 m^2 land for the A-line breeder-seed production plot is sufficient to meet the requirement of 100 000 ha under hybrid (Table 1). This extraordinarily explosive multiplication rate of various classes of seeds of pearl millet means that 1 kg of A-line nucleus seed (adequate for sowing 0.3 ha of a breeder-seed plot) is enough to produce more than 7000 tons of certified hybrid seed, which is adequate for sowing as much as 2.3 million ha (i.e., about 20% of the total pearl millet acreage in India).

Nucleus seed is the basis for all seed classes; hence, it is expected to be the purest seed class. This seed class is the only one that regenerates from itself and needs utmost personal attention from the breeder (Andrews and Harinarayana 1984). It is recommended that each multiplication of the nucleus

seed be done with enough quantity to meet the demand for breeder seed for five years, retaining a portion of the seed from each multiplication for long-term storage as backup stock (Fig. 6). Backup stocks can be used for monitoring genetic changes in the nucleus seed so that timely purification measures can be taken, if required. It is also advisable to keep backup stocks in a different store (perhaps a long-term store, if available) to avoid loss due to natural or human factors.

Andrews and Harinarayana (1984) have suggested that a nucleus seed-production program should not be taken up on an area exceeding 0.2 ha because this class of seed requires the closest attention of the breeder and his staff, who need to scrutinize individual plants at various stages of growth and development. The extent of nucleus-seed production, however, would depend on the size of the breeder's team. Chopra (1982) has suggested planning for production of enough breeder seed in one attempt to meet the foundation-seed requirement for 4-5 years. Such a strategy would depend on the availability of storage and isolation facilities. In any case, the breeder should produce enough breeder seed in one attempt to meet the foundation-seed requirements for at least two years.

Table 1. Land and seed requirements for various seed classes for a target area of >100 000 ha under pearl millet hybrid. Certified hybrid-seed requirement: 100 000 ha x 3 kg ha^{-1} = 300 000 kg.

	A	B	R
Certified hybrid-seed production plot (6A:2R)			
Seed yield: 800 kg ha^{-1}			
Land requirement (ha)	400	-	140
Seed requirement (kg)	1200	-	420
Foundation-seed production plot (6A:2B)			
Seed yield: 600 kg ha^{-1}			
Land requirement (ha)	2	0.7	0.7
Seed requirement (kg)	6	2	2
Breeder-seed production plot (6A:2B)			
Seed yield: 400 kg ha^{-1}			
Land requirement (ha)	0.015	0.005	0.005
Seed requirement (g)	45	15	15

A = Male sterile, B = Maintainor, and R = Restorer to parent.

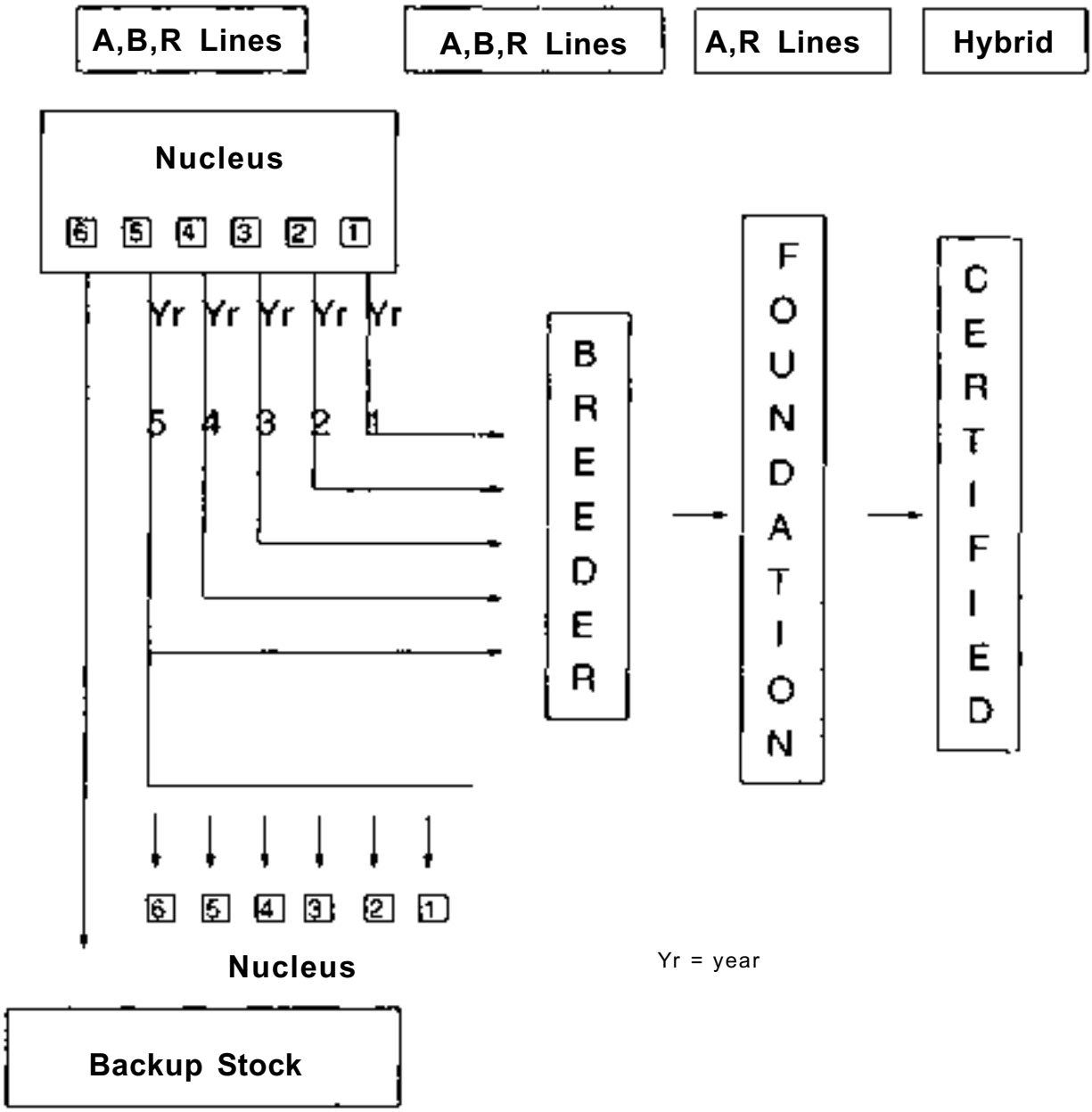


Figure 6. Seed-production stages for parental lines and hybrid in pearl millet.
(Modified from Andrews and Harinarayana 1984)

Development, Production, and Maintenance of Pollinators in Pearl Millet

B S Talukdar

Pollinators are male parents of hybrids. They are bred to impart to the hybrid high grain yield, resistance to downy mildew, and adaptability to a wide range of environments.

Procedure for Breeding Pearl Millet Pollinators

Pearl millet, being a cross-pollinated crop (>85% outcrossing), is available in the natural condition as a random-mating population. Inbred lines can be derived by selfing. Pollinator lines are derived through repeated selfing of plants in an open-pollinated population, random-mating bulk or F_1s derived through planned crossing.

Breeding the inbred pollinator for a single-cross hybrid involves seven to ten generations of selfing. In the process, most inbred lines become uniform in terms of time to 50% flowering, plant height, panicle size, panicle shape, etc. Evaluation and selection for downy-mildew resistance begins as early as at F_3 (Fig. 1).

Three types of breeding schemes are generally followed:

1. Early-generation testing
2. Advanced-generation testing
3. Combination of 1 and 2

In early-generation testing, fertility restoration and combining ability are evaluated at the F_4 stage. Selected F_5 families are evaluated in the field for downy mildew (DM) resistance and are also selfed to produce F_6 lines in the DM nursery.

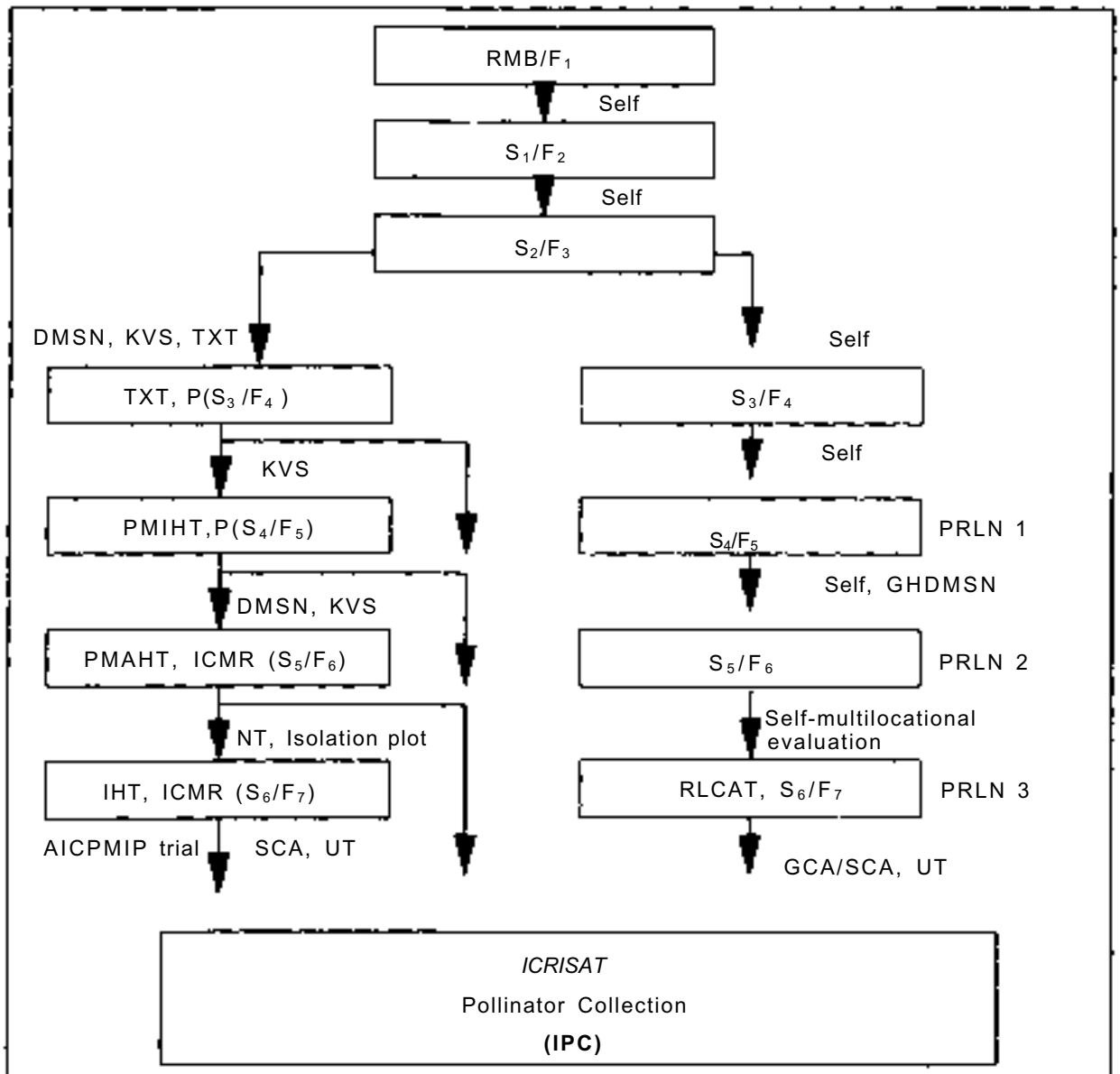
Superior specific combiners are identified at the F_6 stage in the pearl millet advanced hybrid trial (bordered row plot, multilocational trials). Nicking and uniformity tests are conducted at this stage in the dry season at ICRISAT Asia Center, Patancheru.

Hybrids multiplied from the F_7 lines are entered in the All India Coordinated Pearl Millet Improvement Project (AICPMIP) trial and pollinators are entered in the Pollinator Collection.

In advanced-generation testing, individual F_3s are bulk advanced to F_4. Individual plant progenies are generated in F_5. F_5 progenies are evaluated in the greenhouse DM screening nursery. Selected F_6 lines are evaluated multilocationally for plant height, time to flowering, and pollen shedding. Combining ability, uniformity, and nicking tests are done at the F_7 stage. F_7 lines are included in the Pollinator Collection.

In case of certain pollinators, an additional two to three generations of selfing is done to achieve an acceptable level or uniformity before the progeny are included in the Pollinator Collection.

Pollinators from the ICRISAT Pollinator Collection are distributed widely, in response to seed requests. Pollinators supplied to the Indian national program during the last 10 years have provided wide



AHT = Advanced hybrid trial
AICPMIP = All India Coordinated Pearl Millet Improvement Project, India
DMSN = Downy mildew screening nursery
GCA = General combining ability
ICMR = ICRISAT millet restorer
IHT = Initial hybrid trial
IPC = ICRISAT pollinator collection
KVS = Kharif visual season
PMAHT = Pearl millet advanced hybrid trial
PMIHT = Pearl millet initial hybrid trial
PRLN = Potential R-line nursery
RMB = Random mated bulk
RLCAT = R-line combining ability trial
SCA = Specific combining ability trial
TXT = Test cross trial
UT = Uniformity test

Figure 1. Inbreeding and evaluation during pearl millet pollinator development.

diversity. Certain pollinators are preferred more than others by ICRISAT cooperators in India.

Combining ability studies have indicated that most pollinators are good specific combiners. Grain yield evaluation of random samples of pollinators have indicated relatively low grain yield from inbred pollinators.

Currently, the concept of topcrossing is being applied to breeding of topcross hybrids. Topcross hybrids are produced by crossing inbred male-sterile lines with variety pollinators (Fig. 2). Variety pollinators are open-pollinated varieties derived through recurrent selection. Such pollinators are generally high yielding with relatively more stable resistance to downy mildew than inbred pollinators.

Testing of Fertility Restoration

This is done by crossing pollinators with male-sterile lines (A-lines) and growing the F_1. Fertility restoration can be judged on the basis of visual observation of pollen shedding and by scoring it on a 1-9 scale (where 1 = highly effective restorer, and 9 = nonrestorer). It can also be tested by scoring the seed-set under setting bags on a 1-9 scale (where 1 = best seed-set or highly effective restorer, and 9 = no seed-set or nonrestorer).

Desirable Traits of a Good Restorer Line

The desirable traits of a good restorer line are

- Good fertility restoration against a large number of male-sterile lines with different systems of sterility;
- Downy mildew resistance;
- Capability of producing high-yielding hybrids (combining ability); and
- Good pollen shedding in seed production plots in a wide range of environments.

Production of Restorer Parent

Restorer lines of pearl millet can be produced on a large scale in isolation plots. Isolation plots should be approximately 1 km away from other pearl millet fields. Three stages of production are practised in India: nucleus seed, breeder seed, and foundation seed stages. Production of nucleus seed is the responsibility of the breeder; no external inspection is required. Breeder seed is produced by the breeder under inspection by seed certification agencies. Breeders are not involved in foundation seed production.

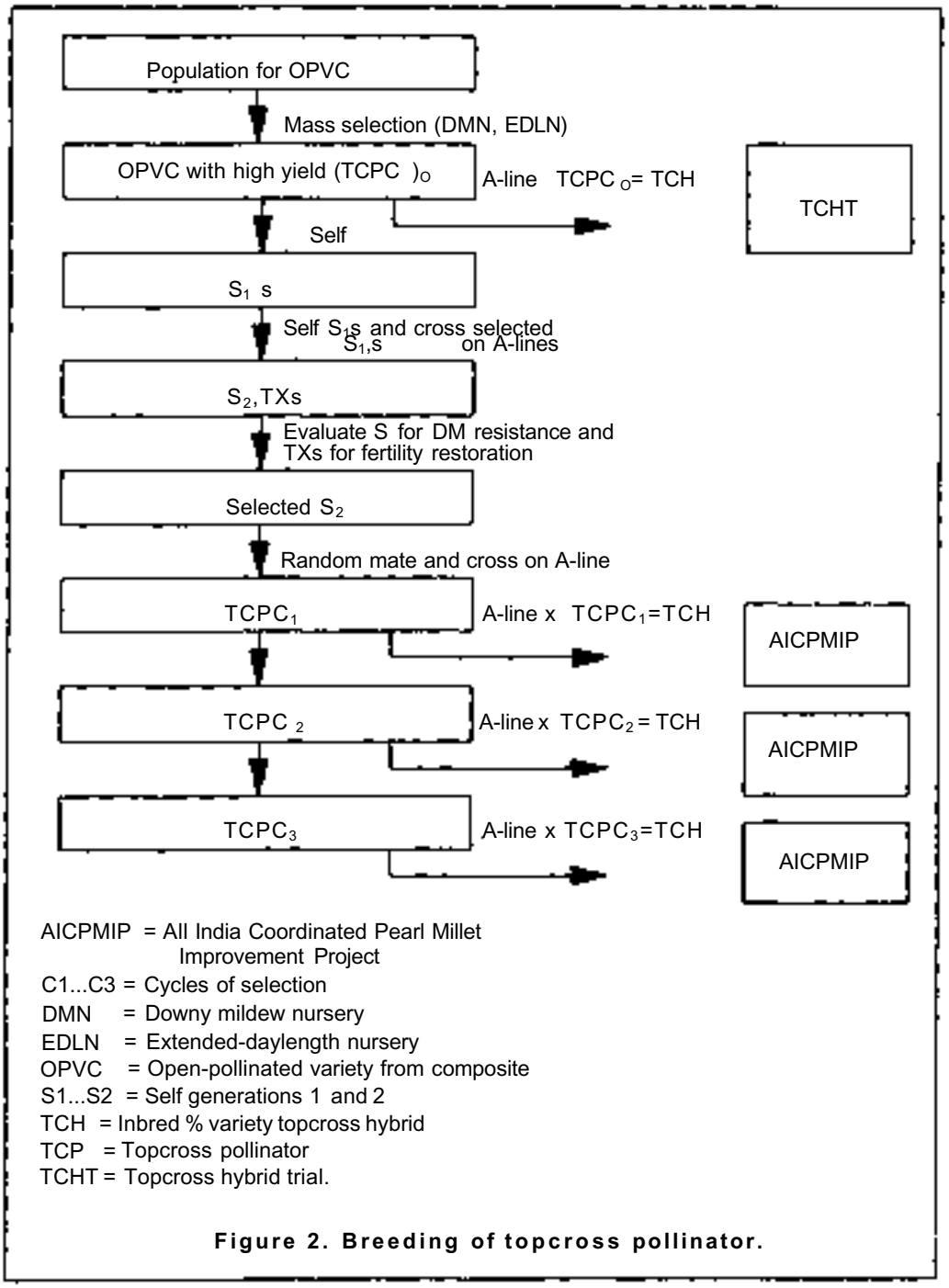
Maintenance of Restorer Parent

Restorer lines can be maintained either by sib-mating (by hand) or by random mating in an isolation plot. They can also be maintained by selfing.

Summary and Conclusion

Pearl millet pollinators in combination with male-sterile lines produce high yielding, downy mildew

resistant, and widely adapted single-cross hybrids in India. Three major types of breeding schemes are followed to breed pollinators: (1) early-generation testing; (2) advanced-generation testing; and (3) combination of (1) and (2). Most of the pollinators bred so far have been good specific combiners. Inbred pollinators are relatively low yielding. Topcross or variety pollinators are being evaluated for the production of high-yielding hybrids. Good restorers should be able to restore fertility against a wide range of male-sterile lines, possess downy mildew resistance, and be good pollen producers in seed production plots. Pollinators can be maintained by sib-mating or by selfing.



AICPMIP = All India Coordinated Pearl Millet Improvement Project
C1...C3 = Cycles of selection
DMN = Downy mildew nursery
EDLN = Extended-daylength nursery
OPVC = Open-pollinated variety from composite
S1...S2 = Self generations 1 and 2
TCH = Inbred % variety topcross hybrid
TCP = Topcross pollinator
TCHT = Topcross hybrid trial.

Figure 2. Breeding of topcross pollinator.

Production of Pearl Millet Hybrid Seed

B S Talukdar

In pearl millet, cytoplasmic-genic male sterility has been exploited in commercial seed production. Details of hybrid seed production have been presented in Khairwal et al. (1990). Most of the seed producers in India prefer not to rely on carry-over stocks because they generally show poor germination if they are not stored well. Moreover, storage also adds to the production cost. Therefore, most of the seed producers in India prefer to take up seed production in the postrainy season. In such a scenario, it is necessary to calculate the amount of hybrid seed required before the seed production program is taken up. However, some producers may not be able to exercise the postrainy-season option due to nonavailability of irrigation water and unfavorable weather conditions.

Steps Involved in Commercial Hybrid Seed Production

The major factors involved in commercial hybrid seed production are choice of location, choice of field, cropping history, isolation distance, male:female ratio, male-line border, nicking of male and female plants, labelling, roguing, crop management, and certification of seed.

Choice of Location

In India, a considerable amount of pearl millet hybrid-seed production is done in the premonsoon or postrainy season in non-pearl millet growing areas using irrigation. Such locations are generally away from fields where pearl millet is grown in the rainy season by farmers. Hybrid seed is produced, processed, and bagged in the same locations that favor raising a good crop of pearl millet under good management. Such locations are preferred by the highly organized seed sector, such as large public or private seed companies. In such a situation, the transportation cost is high and the time available for marketing is very short.

Seed production is also done in the rainy season, which is the main cropping season. In this scenario, seed produced in the previous year is used for sowing. This requires adequate storage facilities, and the capital invested is locked up for a considerable period of time. However, transportation cost is minimized. There is also adequate time for marketing. Generally, small local seed producers prefer this option. Seed produced in the rainy season is also used for sowing in the postrainy season in some pearl millet growing areas where the postrainy-season crop contributes significantly to production (e.g. Gujarat).

Choice of Field

Seed production fields should be of superior quality compared to fields in which the F_1 hybrid is grown by farmers for grain production. They should be adequately isolated from other pearl millet fields. They should be free from waterlogging, and preferably have a light sandy soil. The length of the field should not be too much more than its width.

Cropping History

Cropping history is an important consideration for a seed production plot. This enables the seed producer to plan his fertilizer application. If the previous crop was pearl millet, then the field should not be selected

since there might be a possibility of volunteer millet plants from the previous crop.

Isolation Distance

Pearl millet is a highly cross-pollinated crop. In a still environment, a majority of the pollen grains can travel only a few meters, but under moderate wind velocity (>30 kph) they can travel more than 1 km in the direction of the wind. During the seed production season in India, the wind direction generally changes. The distance travelled by pollen also depends on the presence or absence of physical barriers such as tall, dense vegetation, hedges, buildings, etc. Thus, for the production of hybrid seed, isolation distances range from 500 m to 1000 m depending on the conditions. In many cases, a large number of seed growers multiply the same hybrid in a locality (village) isolated from others. In such a situation, careful planning of seed production helps in maintaining the isolation required for large-scale production.

Male: Female Ratio

The male:female ratio for a hybrid seed production field depends primarily on the pollen-shedding behavior of the male parent and the environmental conditions. Usually, a 1:3 ratio provides good seed-set in diverse environments, ranging from the rainy season in northern India to the postrainy season in southern India. This ratio can range from 1:2 to 1:7.

Male-Line Border

Sowing the male parent (pollinator) on all sides of the hybrid seed production plot ensures adequate pollen for good seed-set on the male-sterile line, and eliminates the possibility of contamination by foreign pollen. This practice is very simple but is rarely followed in hybrid (certified or truthfully-labelled) seed production programs. Probably, such a practice is considered unnecessary because the turbulent wind movement that is often prevalent over large production plots ensures an adequate pollen load within and around the plot. Where pollen shedding is not adequate and the production plot is not sufficiently isolated, a male-line border is useful.

Nicking of Male and Female Lines

The event of shedding abundant pollen by the male line (pollinator) when the stigmas of the female (male-sterile) line are mature and receptive is termed "nicking" in hybrid seed production. Good "nicking" is essential for good seed-set on the male-sterile line. When "nicking" is not good, it can be improved by sowing the male and female lines on different dates. In Andhra Pradesh, pearl millet hybrid seed production is done by raising nurseries of the parental lines by sowing them on different dates and then transplanting both the parents at the same time in the main production field. This practice ensures nicking.

Labelling

In case more than one hybrid is being multiplied at the same time, proper labelling of the parental lines is necessary to avoid transplanting or sowing wrong parental combinations. It is safer to sow one hybrid production plot at a time.

Roguing

Roguing is an important operation in the production of quality hybrid seed. The major aspects of roguing

are: (1) removal of off-type plants from both the pollinator and the male-sterile lines; and (2) removal of pollen shedders from the male-sterile line. Roguing should be done before anthesis to avoid contamination.

Crop Management

In a hybrid seed production plot, crop management involves:

- Proper land preparation;
- Timely sowing;
- Adequate fertilizer and irrigation applications;
- Proper weed control; and
- Control of pests and diseases, if any.

The major objective here is to obtain a high seed yield per unit area. Thus, seed production plots are often good plots and are separated from fields in which F_1 hybrids or other pearl millet crops are being grown by farmers. Seed production is generally done by the organized sector such as seed companies or public sector undertakings, which have adequate means for good crop management.

Certification of Hybrid Seed

In India, certification of hybrid seed is done by seed certification agencies. Production plots of pearl millet hybrids are inspected and certified on fulfillment of the conditions laid down by the agencies in consultation with researchers. Certification of hybrid seed is optional in India; so both certified and truthfully-labelled seeds are sold in the market.

Summary and Conclusion

Pearl millet hybrid seed production at present is entirely dependent on the cytoplasmic-genic male-sterility system in India. The predominant hybrid type produced is the single-cross hybrid. Seed production of pearl millet hybrid is, therefore, straightforward. Timely roguing of off-type plants and pollen shedders is very important to produce quality seed. Crop-management practices are of critical importance in obtaining good returns.

Seed Production of Pearl Millet Open-Pollinated Cultivars

C T Hash

This paper describes procedures appropriate for the maintenance of open-pollinated cultivars and topcross pollinators of pearl millet, regardless of the methods used in developing these genetic materials. The paper concentrates on aspects of genetic purity of open-pollinated cultivars and topcross pollinators. It is assumed that adequate precautions are taken against physical admixtures during sowing (e.g., seed carry-over in machinery or volunteer seed in the soil), harvest, storage, and processing or conditioning.

Open-Pollinated Cultivars and Topcross Hybrids

The principal reasons for the continuing use of open-pollinated cultivars and potential use of topcross hybrids in pearl millet lie in the checkered history of single-cross grain hybrids in India. These hybrids became susceptible to downy mildew, ergot, and smut, and the cost of their seed multiplication was high. The visible variability in pearl millet open-pollinated cultivars and topcross pollinators is a consequence of their variability for many useful traits, including variability for resistance to downy mildew, which is the key to durability of resistance. This range of variability for resistance to downy mildew is very difficult and costly to breed into pearl millet hybrid parental lines. Indeed, marker-assisted backcross programs to attempt this have only recently been initiated at ICRISAT Asia Center. However, genetic variability for downy mildew resistance can easily be carried in breeding populations that serve as the source for open-pollinated cultivars and topcross pollinators. Additionally, the variability in flowering time within an open-pollinated cultivar provides normal protection against ergot and smut infection, due to earlier and more profuse pollen shedding over a longer period than in single-cross hybrids. This variability in flowering time facilitates seed production of topcross hybrids based on variable ("topcross") pollinators, as it provides a wider window of nicking. Finally, variability in flowering time within the pearl millet open-pollinated cultivar or topcross hybrid cultivar contributes to superior stability of grain and stover yield across environments. This provides greater opportunity for escape and/or recovery from both drought and pollen wash than is offered by the uniform single-cross hybrid cultivars.

The second reason for continuing with improved open-pollinated cultivars of pearl millet is that their seed multiplication is technically simpler than that of hybrids. This facilitates secondary spread of such cultivars via local seed systems, and provides a mechanism for continued evolution of the crop in farmers' fields. The role of local seed multiplication and the need for continued involvement of farmers in the development of their own cultivars is especially important in remote and heterogeneous regions that are poorly served by the formal seed system (Almekinders et al. 1994). It is probably critical to maintenance of local adaptation and yield stability in many of the more marginal pearl millet production environments. Heterogeneous open-pollinated cultivars and topcross hybrid cultivars are appropriate for such harsh and isolated areas. Millions of hectares in southern Asia, and in western, central, and southern Africa are annually sown to open-pollinated cultivars. These cultivars are often farmers' landraces, but increasingly, improved open-pollinated cultivars are being adopted. These open-pollinated cultivars are grown because they are well suited to the vast regions where traditional agricultural practices are still the rule. In these areas, hybrid seed distribution channels are not sufficiently flexible to accommodate the season-to-season variation in seed demand. In the arid and semi-arid environments where pearl millet is traditionally grown, these genotypes meet farmers' needs better than any other available alternative.

Improved open-pollinated cultivars and topcross pollinators have several features that make them more appropriate:

- Maintenance and seed multiplication of improved open-pollinated cultivars, topcross pollinators, and to a lesser extent topcross hybrids, is relatively simple compared to that of single-cross hybrids based on inbred parental lines. Seed production targets for open-pollinated cultivars can be achieved easily and rapidly on relatively small production areas.

- Open-pollinated cultivars derived from an ongoing population-improvement program can replace older varieties, either as new cultivars or as improved versions of the existing cultivar. An example of this in pearl millet is the replacement of the original Okashana I in Namibia (ICTP 8203) with ICMV 88908 released in 1989 (Witcombe et al. 1995).

- Seed production costs for open-pollinated cultivars (all seed classes) and topcross pollinators (nucleus-, breeder-, and foundation-seed classes) are relatively low as smaller areas are required to multiply a given quantity of seed on their vigorous, high-yielding plants than would be required for multiplication of single-cross hybrids on their relatively weaker inbred seed parents. Thus, seed quantities can be built up rapidly and economically.

- Open-pollinated cultivars have a distinct advantage in areas where seed distribution is difficult and costly. The seed of open-pollinated cultivars can move from farmer to farmer and can be saved by the farmer from season to season. Both of these factors have a multiplicative effect on the area covered by a particular cultivar.

- Exchange of improved germplasm among national programs, and between the public and private sectors of these national programs, is easier with open-pollinated materials than with closed-pedigree materials, which might involve proprietary rights.

- There are greater opportunities to exploit genetic variability within the introduced open-pollinated cultivars and topcross pollinators than exist within the inbred parental lines of single-cross, three-way, and double-cross hybrids. This facilitates reselection to meet requirements for local adaptation and adoption.

Open-Pollinated Cultivars

The term "open-pollinated cultivar", or "variety", for a cross-pollinated crop originally meant a self-reproducing population of plants that, although not genetically identical, exhibit unique, recognizable, and stable associations of traits. The term has more recently been redefined as a superior fraction of a population that is different, relatively uniform, and stable. Such a variety is different because it possesses a combination of traits that distinguish it from other known cultivars and define its identity. In pearl millet, the following types of base populations of improved open-pollinated cultivars are possible: landrace cultivars, synthetic varieties initially produced by intermating inbred parents, varieties resulting from long-term mass selection, experimental varieties constituted from elite progenies identified during a program of recurrent selection, and the various intermediates possible among these four groups. An improved open-pollinated cultivar can be readily identified and maintained, and is more likely to be multiplied and widely adopted by farmers. A successful open-pollinated cultivar of pearl millet is likely to have reduced variation for significant agronomic traits (50% flowering, tiller number, panicle dimensions, plant height, and grain mass), and should be relatively stable in terms of expression of these traits over time. It should not exhibit variation beyond the acceptable standards fixed for different traits. Experimental

varieties that are constituted by recombining 8-15 selected families from a family-structured population can be sufficiently uniform in appearance provided care is exercised in selecting families that are similar in maturity, plant height, tillering, and panicle characters.

An open-pollinated cultivar should be an assemblage of plants having relatively uniform phenotypes and representing a superior fraction of a population that has undergone some degree of improvement. Selection of superior families for constituting an experimental variety may be necessary even in populations that have been subjected to several cycles of improvement, especially if the gross plant architecture of the base population is similar to that of an existing adapted open-pollinated cultivar.

Characterizing an Open-Pollinated Cultivar or Topcross Pollinator

Once an open-pollinated cultivar has reached the release stage, it should be described for salient features in the area of its adaptation. Similarly, once a topcross hybrid has reached the release stage, it and its parents should be described. For topcross pollinators, the description required is essentially identical to that required for an open-pollinated cultivar. If the seed production and seed-purity evaluation environments are likely to be markedly different from the environments in which the grain crop is to be produced, it may be helpful to develop a separate varietal description of the open-pollinated cultivar or hybrid parental population for these environments as well. This will reduce the likelihood of a genetically genuine seed-lot being rejected by seed-certification officials due to an environmentally-induced departure from the varietal description.

An important attribute of a good open-pollinated cultivar or topcross pollinator is uniformity. However, open-pollinated cultivars and topcross pollinators will seldom be as uniform as even the most variable of single-cross hybrids. Even though an elite fraction of the population is recombined to produce the open-pollinated cultivar or topcross pollinator, it will show some variation for several important agronomic characters. The morphological traits and range of variation expected within an open-pollinated variety or topcross pollinator must be adequately described to serve as a guide for its maintenance and seed certification.

Seed-certification standards should be fixed carefully for various stages of seed multiplication to provide quality control—not to hamper seed production and distribution. The standards set for pearl millet open-pollinated cultivars and topcross pollinators should not be too stringent—indeed, they should be considerably relaxed compared with those set for the genetically uniform, inbred parental lines of hybrids. They should be realistic (not idealistic), enforceable, and appropriate for the conditions prevailing in a given country.

Characters such as adaptation, plant height, panicle length and girth, crop duration, grain color, grain texture, grain size, panicle pigmentation and bristling, plant architecture, and tolerance or resistance to pests and pathogens should be considered in varietal descriptions.

Each open-pollinated cultivar or topcross pollinator released should have some distinct genetic feature(s) that can be used to distinguish it from others. Attributes such as pigmentation and pubescence of various plant parts, degree of panicle bristling, panicle length and girth, seed shape and color, and degree of internode condensation can be considered for characterization. A list of traits that can be used in describing an open-pollinated cultivar or topcross pollinator is given in Table 1. When quantitative characters are used as varietal descriptors, the expected mean, range, and standard deviation from the mean of the various classes should be given to indicate the acceptable variation within the cultivar or topcross pollinator. For qualitative characters, the expected variants may be given in percentages (e.g.,

leaf blade smooth, hairy leaf blade not exceeding 5%). It is also useful to include in the varietal description a short list of off-type trait combinations that are not expected to occur at all except as a result of physical admixture, the presence of volunteer seedlings, or pollen contamination.

Table 1. Plant characters for potential inclusion in the varietal description of a pearl millet open-pollinated cultivar or topcross pollinator.

	Characters	
Plant part	Qualitative	Quantitative
Seedling	Coleoptile color Seedling color	Vigor
Stem	Dwarf/tall Internode color Intemode hairiness Node color Nodal ring of hairs	Height Number of nodes Number of tillers - Primary, Secondary, Tertiary
Leaf	Auricle color Blade color Margin color Midrib color Sheath color Blade hairiness Margin hairiness Sheath hairiness	Main stem leaf number Flag leaf length Flag leaf width Fourth leaf length Fourth leaf width Leaf angle
Panicle	Stigma color Fresh anther color Dry anther color Glume color Glume cup color Bristling - Color, Shape, Compactness	Diameter Length Number plant^{-1} Ratio of diameter to length
Seed	Pericarp color Endosperm color Endosperm texture Shape Color in $FeSO_4$ test Color in phenol test Color in modified Phenol tests $CuSO_4$, 0.4% Na_2CO_3, 0.6%	Length Width 1000-seed mass

Quantitative descriptors will be of value in the maintenance of open-pollinated cultivars and topcross pollinators, and in the production of breeder seed. In subsequent stages of seed multiplication and for certification standards, it is the qualitative characteristics, especially those listed for off-type plants, that should be used as guidelines. A pearl millet open-pollinated cultivar or topcross pollinator should show little change in its phenotypic attributes relative to those of other released materials when reproduced in its area of adaptation for maintenance and/or seed increase from one stage to another. Phenotypic stability is highly desired, because only a stable material will perform in accordance with expectations from year to year and season to season.

Maintenance and Seed Production

Procedures for the maintenance and seed production of open-pollinated cultivars and topcross pollinators vary slightly with the stage of multiplication—reflecting the principle that extra care is needed to maintain the identity of the material during the early stages, and that there should always be an onward flow from stage to stage. Only nucleus seed, which is used tor sowing breeder-seed plots, should regenerate itself, and that should be under rigorously controlled conditions.

Pearl millet is more easily contaminated by outside pollen because of its protogynous flowering habit. Further, the pollen of pearl millet is more robust. It can survive a greater degree of desiccation and can travel farther with the wind, on insects, or even on the clothing or bodies of people. Therefore, during the first or second day of flowering, a pearl millet field is most vulnerable to any external pollen, especially windborne pollen, because little pollen is being produced within the field.

The need for an appropriate isolation distance for multiplication of seed of open-pollinated cultivars and topcross pollinators is recognized. The permissible levels of off-type plants in such materials can be higher than in cultivars of self-pollinated crops or hybrid parental lines. This is because (a) cultivars of cross-pollinated crops have a higher "buffering capacity" for off-type effects as a natural consequence of their heterozygous and heterogeneous population structure; and (b) if good isolation distance has been maintained, most of the off-types observed will have arisen through recombination of genes already present and not from the introduction of alien genes.

Multiplication rates in pearl millet are high, particularly with open-pollinated cultivars and topcross pollinators. Three to four kg of seed are more than sufficient for sowing one hectare, and for producing 1000 kg of clean seed, even under conditions of short days, cool temperatures, and moderate soil fertility. Thus, three stages of seed multiplication (breeder, foundation, and certified) are generally sufficient for multiplication of open-pollinated cultivars. Note that in the case of topcross pollinators, the certified seed class does not exist as the foundation seed class of these materials is used in the production of the certified seed of topcross hybrids.

Nucleus Seed

The nucleus seed maintained by the breeder is the seed stock from which all other seed classes are derived. It is not subject to certification. However, it is the basic stock and requires special attention. Nucleus seed should be the only stock that regenerates itself. It should not be regenerated every year unless inadequate seed-storage conditions necessitate this. Regeneration of nucleus seed once in four years is recommended. The produce of a nucleus-seed plot should be thoroughly dried, treated against insects (naphthalene at the rate of 100 g per 10 kg of seed will render the seed unattractive to storage pests), and divided into six lots of 5-10 kg each. These lots should be kept in hermetically sealed containers in a cool store, if available. Lots 1,2,3, and 4 are used to sow breeder-seed plots for the next

four years; lot 5 is used to sow the next nucleus-seed plot four years hence; and lot 6 is a backup or insurance lot that should be kept in a different building than the other lots.

Mass selection in isolation. This is the preferred method of production and maintenance of nucleus seed of open-pollinated cultivars and topcross pollinators. Nucleus-seed plots should be grown in isolation at least 1500 m away from any other plot of pearl millet, wild pearl millet, or elephant grass (*Pennisetum purpureum*), preferably in the off-season when crop growth and seed quality will be excellent. The crop should be thinned at an early stage to evenly-spaced single plants (or sown in hills and thinned to single plants), using only one-third of the normal commercial plant population so that differences in individual plant expression are maximized. Several inspections prior to flowering are recommended. Off-type plants should be removed by uprooting (roguing). Cutting such off-type plants at ground level is not acceptable as many will produce ratoon tillers that can contaminate the production plot. During flowering, daily inspections are needed to identify and remove all plants suspected of being not true to type before they shed pollen. Care should be taken during inspections at flowering to visit the nucleus-seed plot before—not after—visiting other pearl millet plots in order to minimize contamination by pollen borne on the bodies and clothing of the roguing crew. A final roguing should be conducted in the standing crop before harvest to eliminate any remaining off-type plants. To ensure that the varietal norms do not change due to genetic drift, nucleus-seed plots of open-pollinated cultivars and topcross pollinators should not be less than 0.1 ha, and should contain at least 3000 plants. On the other hand, such plots should not exceed 0.2 ha because it is difficult to scrutinize all plants daily in large plots.

Bulk pollination. This method of maintaining and producing pearl millet nucleus seed may be undertaken when an isolation distance of 1500 m is not possible. However, in this method it is preferable to maintain an isolation distance of several hundred meters during flowering in order to minimize the risk of pollen contamination. The cost of labor and supplies is much greater in this method than in an isolated mass-selection plot. Sow the nucleus-seed bulk to obtain about 8000 spaced plants. Select about 3000 plants that fit the phenotypic varietal description, and cover all panicles possible on these plants with setting bags. Collect bulk pollen from the selected plants and pollinate them using this bulk. To reduce inbreeding, this may be done by collecting pollen from the odd-numbered rows and pollinating the even-numbered rows, and reversing this procedure every alternate day during flowering. At harvest, select hand-crossed panicles from about 1000 plants that have the desired panicle and grain characteristics. Bulk equal quantities of hand-crossed seed from each of these plants to produce the nucleus seed. The quantity of nucleus seed produced by this method can be manipulated by varying the number of harvested plants and the quantity of hand-crossed seed sampled from each. Breeder seed may be obtained by bulking the hand-crossed seed produced on the remaining plants not harvested for nucleus seed.

Isolated bulk sowing converted into half-sib crossing block. Establish about 12 000 plants in rows in an isolated plot sown with bulk nucleus seed. Prior to first panicle emergence, arbitrarily designate rows as male or female in the ratio of 1 male row to 2-4 female rows. Cover the panicles in the female rows with setting bags. Undesirable and off-type plants in the male rows (as many as 20-40%) should be uprooted. Collect bulk pollen daily from the male rows and use it to cross onto receptive panicles in the female rows. In this manner, better control can be exercised over the pollen source in the male rows used as pollinators. The male rows provide a good indication of the environmental variation in the field, which in turn facilitates selection within the female rows of plants conforming to the varietal description.

Prior to harvest, treat each 5 m of a female row as a grid. Select 3-5 plants that meet the varietal description, and harvest two or three hand-crossed panicles from each grid. About 1000 panicles can be selected in this manner to serve as sources of the next generation of nucleus seed. A bulk sample of

seed from these panicles and/or additional hand-crossed panicles from the selected true-to-type female plants could provide the breeder seed.

Isolated half-sib panicle-to-row plot. This is a simple and effective system for maintaining an open-pollinated cultivar or topcross pollinator of pearl millet and for producing both nucleus seed and breeder seed. It requires isolation and can be initiated with seed from individual panicles harvested for nucleus seed following any of the methods discussed above. It involves the following steps:

- Selected half-sib panicles (500-1000) are individually threshed. The following season, these are sown as half-sib female rows in a well-isolated plot. The female rows are sown alternately with rows of a balanced male bulk constituted by mixing equal seed quantities from each half-sib panicle.

- Prior to flowering, any female half-sib rows having off-type plants are removed. Similarly, off-type plants in the male bulk are rogued out as they are identified.

- Prior to harvesting, about 50% of the female rows that best conform to the varietal description are selected. The male rows serve as controls for the selection of female rows. From each of the selected female rows, panicles from 2-4 plants are harvested to serve as nucleus seed for future increase and maintenance. If the requirement for breeder seed is small, it may be possible to take a bulk sample from these selected panicles to provide breeder seed. If larger quantities are required, breeder seed may be harvested from the remaining true-to-type plants in the selected female rows.

Breeder Seed

The responsibility for maintaining the purity of breeder seed, as long as the open-pollinated cultivar or topcross hybrid is in production, should rest with the breeder. When a released cultivar is replaced by a superior one, and when replacement is well underway, then breeder seed maintenance of the replaced cultivar or its parental stocks can be discontinued. However, the seed should be contributed to a suitable germplasm collection, if that had not been done earlier, in order to ensure that viable seed is available in future, should the need for it arise.

The quantity of breeder seed produced can be regulated by increasing the number and length of the rows in the breeder seed production plot. However, in order to maintain the highest level of genetic identity, the breeder-seed plot should be small and manageable. These plots should be grown in the off-season at less than normal plant population, and in extremely good isolation (more than 750 m from other flowering pearl millet plots from the time of first panicle emergence until harvest). Both isolated mass-selection and isolated half-sib panicle-to-row methods described above for nucleus seed production are appropriate for breeder seed production. The plots should be thinned to spaced plants and rogued daily during flowering. Good roguing at this stage can greatly reduce the need to do further roguing in the later stages. Not more than 1 % of off-types should be permitted at final inspection. The plot size can be 0.1-0.5 ha, depending on the quantity of breeder seed required to produce the targeted quantity of certified seed. Assuming a very conservative multiplication factor of 200 per generation, one can make the necessary calculations as given in Table 2.

Table 2. Estimated areas required for seed multiplication of different seed classes of a pearl millet open-pollinated variety necessary to sow 1 m ha.

	Breeder seed	Foundation seed	Certified seed
Area	0.1 ha	25 ha	5000 ha
Quantity	100 kg	20 t	4000 t

Thus, 100 kg of breeder seed of an open-pollinated cultivar, produced from 0.5 kg of nucleus seed of the same cultivar, can easily meet the requirement for the production of certified seed necessary to sow 1 m ha. In fact, with vigorous cultivars grown under good management conditions, it is possible to achieve a seed-multiplication rate two or three times higher.

Foundation Seed

The first increase from breeder seed is referred to as foundation seed. The responsibility for producing foundation seed often rests with a seed production agency, but it may call for assistance from the breeder(s) responsible for maintaining the identity of the cultivar or hybrid parent. Only certified breeder seed should be used to sow foundation seed plots. Breeder seed can be used to cover a larger area for foundation seed production if it is first sown to a small nursery and the seedlings are then transplanted at appropriate spacing into the seed multiplication plot. The foundation seed plot should be sown on uniform land at least 1 km from the nearest pearl millet plot, preferably even farther if sown in the direction of the wind. With the same seed, first sow a border 4 m wide around the perimeter of the plot 4-7 days before sowing the center. The purpose of this perimeter sowing (from which the seed will be separately harvested and sold as grain) is to provide pollen by the time the plants in the center begin to come to flower. This provides protection, based on dilution, against incoming windborne pollen from other fields. Before flowering, search for and destroy any volunteer pearl millet plants on the field borders and in ditches, and in nearby crop land. Rogue the obvious off-type and downy mildew plants as they are detected, preferably before flowering, to meet foundation seed standards. As many as 10-15% of the plants may have to be rogued out, but this fraction will be lower in foundation seed plots sown with breeder seed from well-rogued plots. In foundation seed plots, maintenance of the genetic identity of the open-pollinated cultivar or topcross pollinator should be emphasized. These plots should be closely monitored by persons responsible for the production of foundation seed.

Certified Seed

Certified seed is the last stage of seed multiplication. It should be produced by select seed growers or at seed farms, and its production should be coordinated and supervised by public or private seed agencies responsible for seed multiplication and distribution. The seed specialists and seed certification agency should assist growers in the production of good quality certified seed. Slightly lower-than-optimum plant density for the seed crop may be used as this helps achieve better seed quality.

Certified seed of open-pollinated cultivars should be produced only from officially approved foundation seed, and should be sown in large contiguous blocks—preferably in an area where other pearl millet plots have not been sown. There should be an isolation distance of at least 400 m. It may be

possible to ensure that pearl millet-producing farmers in the vicinity of the certified seed production plots are given—and agree to grow—the same cultivar as that being multiplied. Rogue off-type and diseased plants if possible, inspect (making sure that plants not conforming to the varietal description do not exceed 5% at the final inspection), certify, condition, and treat with insecticides and fungicides before bagging for sale to farmers.

Truthfully-Labelled Seed

In India, "truthfully-labelled seed" is sold on the strength of the cultivar name and the brand name of the producer rather than having its identity guaranteed by the government seed certification agency. The legal requirement is that it be grown with an isolation distance of at least 10 m from pearl millet plots of the same cultivar that for some reason fail certified seed standards. The truthful label provides a mechanism by which private and public seed agencies can market produce that fails to meet the strict standards for certified seed, and thus limit losses from such seed production plots. It also provides these organizations a means to market seed of cultivars that have not completed requirements for formal release by government authorities. This is welcome when it permits a broad array of good proprietary products to reach farmers earlier than would be possible following official procedures for cultivar testing and release.

Standards for Maintaining Varietal Uniformity

As an open-pollinated cultivar or topcross pollinator goes through different stages of seed multiplication, it is likely to become more and more variable. In open-pollinated cultivars of maize, CIMMYT (1984) suggests that in maintenance of breeder seed the selected families should fall within ±0.7 standard deviations of the varietal mean. In foundation seed plots, plants differing from the varietal mean by more than ±1.5 standard deviations should be removed. If it is possible to carry out roguing in the certified seed production plots, plants falling more than ±2 standard deviations from the varietal mean should be removed. These standards appear to be appropriate for pearl millet as well, assuming "eyeball" estimates of the deviations of plants from the varietal mean. Table 1 indicates suitable plant characters for inclusion in the varietal description of pearl millet open-pollinated cultivars. For example, any plant that is clearly shorter and later or earlier flowering than average can safely be rogued out. However, strict numerical adherence to these standards for the purpose of pearl millet seed certification would not be appropriate.

Seed Multiplication by Farmers

With open-pollinated cultivars, it is possible for farmers to produce their own seed. It is preferable, for maintenance of varietal identity, that it is done only from crops grown directly from certified seed. Although some outcrossing with other pearl millet is likely to occur when farmers multiply their own seed, multiplication by them helps very much in promoting the wider use of improved cultivars. Because many farmers will multiply their own seed anyway, it is helpful to provide advice to them—in their local language, if possible—to assist them in obtaining seed that is as genuine and as vigorous as possible. Points that should be noted include:

- Where irrigation is possible, a small off-season seed multiplication plot will give excellent isolation from contaminating pollen of other pearl millet. In the normal crop season, very early sowing is desirable, in fields at least 400 m from fields of other pearl millet cultivars. In either case, multiplication should only be taken up in fields that did not have a pearl millet crop the previous season.

- Select panicles for seed from standing plants in the field, before the general harvest.

- Collect panicles for seed only from the middle portion of the field, providing at least 10 border rows on all sides. This does not apply to small off-season irrigated plots.

- Choose panicles with clean, well-formed grain from typical, average plants. Do not harvest seed from early, late, extra-tall, or diseased plants. The best plants are likely to be outcrosses, so it is best to leave seed from them in the field if you are to retain the typical performance of the cultivar.

- Choose at least 500 panicles, and dry them thoroughly. Thresh these panicles in a specially cleaned place to avoid contamination with other seed. Treat the seed with insecticide and store it in sealed containers, with labels inside and outside.

- If the performance of the improved cultivar is to be maintained, it is advisable that farmers only grow their own seed for one generation after purchase of certified seed. Thus village-level farmer-seed multipliers should buy and sow 1-2 kg of certified seed every year to generate seed for their own use and for sale to their neighbors.

Other Considerations in Planning Seed Production

If good quality seed is to reach farmers on time and in the quantities needed, it is necessary to do more than simply follow the proper procedures for maintenance and seed production. It is also necessary to maintain reserve stocks, to multiply the seed in appropriate environments, and to develop guidelines to determine how much seed of each cultivar should be produced.

Reserve Stocks

In any seed production program, the need to save and store enough reserve seed is well recognized. This guards against losses resulting from crop failures or other disasters. Reserve stocks help ensure continuity of a seed multiplication program. There should be enough nucleus seed in cold storage (preferably at two different places) to sow at least two nucleus seed multiplication plots of appropriate size. Similarly, there should be reserves of breeder seed and foundation seed adequate for sowing at least two generations.

Location of Seed Multiplication Fields

If open-pollinated cultivars and topcross pollinators are multiplied in areas outside their zone of adaptation, rapid shifts can occur in their genetic makeup, phenotypic characteristics, and performance. Thus, maintenance of their nucleus seed, and multiplication of breeder seed and foundation seed, is best taken up in environments that permit reproduction of all plants. Plots of these seed multiplication stages should be located in an area to which the pearl millet genotype is adapted. Since pearl millet is generally grown under dryland conditions during the rainy season, rain at harvest is an ever-present risk when this procedure is adopted in order to maintain the genetic identity of these open-pollinated genotypes. Arrangements should be made for artificial drying of panicles harvested from nucleus seed, breeder seed, and foundation seed plots, where possible, in order to ensure that the physical quality of the harvested seed is also maintained. Maintenance of local adaptation is generally well taken care of when seed is multiplied locally for farmer-to-farmer sale or exchange, outside the formal seed system. This restriction on the seed multiplication environment is less important for certified seed. The maintenance and

multiplication of different classes of seed in their area of adaptation, and under appropriate management, also helps provide larger quantities of seed.

Guidelines for Determining Seed Requirements

To avoid shortages or surpluses of seed, it is important to plan reasonable and adequate seed multiplication. The requirements of different seed classes should be known in advance for each cultivar and parent. It can be calculated as per details given in Table 3. The following factors should also be considered:

- Area to be covered by a released cultivar based on its adaptation and available alternatives;
- Seed-replacement interval—one year for hybrids and one to three years for open-pollinated cultivars;
- Seed generations required to produce certified seed;
- Pdtential requirements for certified seed—this determines requirements for foundation seed and breeder seed;
- Land requirements for production of different seed classes; and,
- Seeding rate (lower than that used in commercial grain production) for production of breeder seed, foundation seed, and certified seed.

Conclusion

Multiplication of seed of open-pollinated cultivars and topcross pollinators of pearl millet is relatively simple as the cultivars are vigorous and the seed multiplication rates are high. Maintenance of adequate isolation distance, and management of labor operations to minimize pollen movement between seed multiplication plots of different cultivars is critical if true-to-the type seed is to be produced. When breeder seed is used for multiplication of foundation seed, or its equivalent, prior to certified seed multiplication, pearl millet breeder seed requirements are small, and the nucleus seed class is not necessary. Therefore, procedures indicated for nucleus seed production can be followed for production of breeder seed itself. If sufficient care is taken in the nucleus seed, breeder seed, and foundation seed stages of multiplication, little roguing will be required in the certified seed production plots. Farmers can multiply their own seed of open-pollinated cultivars, and should be encouraged to do so in a way that the genetic integrity of the cultivar is maintained.

Seed-Processing Techniques and Chronology of Indian Seed Industry

Production of Foundation and Certified Seeds of Sorghum and Pearl Millet

V Jaya Mohan Rao

The strength of crop production programs depends on the success of seed production programs. In the absence of good-quality seeds, the investment on other inputs may not bring about the desired results. This chapter deals with the organizational structure and planning required for production of seed, seed certification standards, and seed-processing procedures.

Organizational Setup

It is necessary to have an apex seed organization at the national level which monitors the seed programs in the country, takes care of training needs, and functions as a nodal agency for seed buffer stocking and other special schemes.

Each state should have a seed corporation that looks after the seed requirements of farmers in that state. Initially, such corporations can be set up in a few important states, and after watching their performance, similar corporations can be established in other states, incorporating suitable modifications, if necessary. These corporations must not only have a service function but must also be self-supporting. These state corporations should produce and supply seeds to farmers in the state. Seed produced in other states can be obtained through the national organization or by direct arrangement with other state corporations.

Each state corporation must decide about its product mix. For profitability, it can produce high-value, low-volume seeds, e.g., hybrid seeds of different crops (cotton, millets, oilseeds, vegetables, etc.) besides producing seeds of self-pollinated crops as a social obligation to farmers.

Seed may be supplied to different agencies upon full payment of cash, or alternatively, upon payment of 50% cash supported by a bank guarantee for the other 50% of the amount. Seed should not be sold on a consignment basis. Timely positioning of the seed in the market at least 30-40 days ahead of the sowing season in the consuming centers is very important. A plan for the supply of seeds and an estimate of seed requirement based on the seed-replacement rate should be prepared.

Seed Subsidy

To popularize the use of newly-released varieties/hybrids, it is necessary to provide a subsidy on certified seed at source. This will promote the use of certified seed which will in turn help increase crop production.

Import and Export of Seed

The parent material for producing varieties/hybrids suitable to a country may have to be imported from other countries. To meet the immediate demand, the finished products of superior varieties/hybrids can be imported after preliminary testing by research institutions and after conducting test marketing. India implemented a New Seed Policy in October 1988, liberalizing the import procedures for seeds.

Seed production of promising varieties can be taken up by the importing countries if they have strong national and state production programs. Alternatively, some countries can take up production in collaboration with foreign companies. The National Seed Corporation, a Government of India organization, extends assistance to other developing countries in formulating seed projects.

If the climatic conditions permit it, a country can take up production of seeds of hybrids, ornamental plants, oilseeds, vegetables, fibre crops, etc. These seeds can also be produced for export, after formulating a suitable seed policy.

Planning

Seed production programs should be taken up in areas that are suitable for production of good-quality seeds. The seed plots must have the required isolation distances in order to maintain the purity of the seed. Seed production projects may be taken up in collaboration with enterprising farmers in areas where seed yields are high and it is more economical to do so.

The seed production program should be concentrated in a few clusters of 2-3 contiguous villages with about 200 hectares. The number of such clusters to be included in the program depends on the total seed requirement. Using compact blocks for seed production involves fewer isolation problems and makes supervision and maintenance of quality easy. Such clusters will also solve the nicking problem to a large extent, and can also serve as demonstration blocks.

Seed production programs should be so planned as to make certified seed available at least 35-45 days before the beginning of the sowing season. To ensure this, it is necessary to fix a target date for each step of the seed production process, i.e., procurement of seed from the seed producing farmers to processing, certification, and packing.

During processing, the seed must be thoroughly dried. Excess moisture may lead to pest infestation, fungal development, deterioration in quality, and loss in germination. The seed must be packed suitably (cloth bags, polythene pouches, cartons, tins, etc.) to hold sufficient seed to sow 0.2 ha or 0.4 ha as per the preference of the farmers.

It is desirable to have more small processing plants of 1000-20 000 tons capacity rather than one with large-capacity. Such plants should be established near the seed-producing areas to save on transportation and facilitate supply to farmers well before the crop season begins. The processing plant should have enough space to store at least 50% of the capacity of the plant at any given time. Maintenance of stocks and fumigation against storage pests will be easier, and overhead expenditure will be minimized. The processing plant must have a quality-control laboratory.

Seed can be stored in transit godowns or at the processing plant itself before despatch. It is necessary to store the seed in a dry place. Seed stored in a humid area will lose germination faster; therefore, it should be shifted to a dry place immediately after processing and bagging. Seed bags must

be stacked on wooden pallets. Care must be taken to see that the number of stacks of seed bags does not exceed the recommended limit so that the germination of seed in the lower bags is not affected. The seed must be protected by spraying the following insecticides at regular intervals:

Malathion® 50 EC: 1 part:300 parts of water; apply @ 3 L 100 m^2 of surface area. DDVP® (0.25%) 2.5 mL in 1 L water; spray 100 m^{-2} space.

In addition, fumigations are done with aluminum phosphide with a dosage of 1 tablet of 3 g ton^{-1}, under airtight conditions. This dosage can be increased to 2 tablets ton'^{1} if the godowns required to be fumigated are reasonably airtight.

Procurement of Seed

Estimation of seed demand is a complex matter. It depends on seasonal conditions, particularly rainfall pattern, prices, varietal preference, seed availability with farmers, marketing and distribution channels, packing size, natural calamities, etc.

To estimate the seed requirements for different crops in a state/country, the probable replacement rate of seed of each crop should be determined, i.e., a decision has to be taken by the government with regard to the percentage of the area under high-yielding varieties of each crop for which seed is to be supplied. For example, in a self-pollinated crop like rice in Andhra Pradesh (India), farmers prefer to replace their seed after every three years. Thus, the seed replacement rate for rice would be 33% i.e., sufficient seed must be supplied every year to cover 33% of the total area under high-yielding varieties of this crop. Besides assessing the seed requirement on the basis of the seed replacement rate, realistic seed demand can be assessed through different channels.

Seed demand can be assessed with the help of the Department of Agriculture, seed dealers, cooperatives or allied societies that deal with seed. The amount of carry-over stocks available in the country should also be estimated. This estimate should be done by the seed-monitoring division of the central government. The assessment of local requirement of seed can be done with the help of village-level agencies that distribute other inputs like fertilizers to the farmers. It will be easy for such agencies (e.g., cooperative society) to find out the required quantity of seed, variety-wise. The village level information can be sent up to the district level, and onward to the state-level authorities. The seed requirements of various crops in each state can thus be assessed and compiled by the state administration.

Buffer Stock

It is necessary to keep a buffer stock of seed to meet contingencies such as natural calamities and to safeguard against shortfalls in seed production.

The quantity of seed to be kept in buffer should not be less than 10% of the projected requirement in the subsequent year in the case of certified seed, 20% in the case of foundation seed, and 50-100% (depending upon the hybrids/varieties) in the case of breeder seed. In the seed industry, the quantity of carry-over stocks must be kept at a minimum.

The operational expenditure (local transportation of seed, storage cost and interest charges, and also the difference in cost in case the seed is to be sold as grain) is to be borne by the central government. This will help in the successful implementation of overall crop-production programs during

national calamities.

Certification Standards

Sorghum

The production and handling of foundation seed and certified seed must be supervised and approved by the certification agency. The seed must meet the standards prescribed by the certification agency.

Eligibility Requirement for Certification

- Seed of varieties and hybrids meant for certification should be from a source that is reliable and approved by the certification agency.

Land Requirements

- The seed production field offered for certification should be irrigated at least three weeks before sowing, and plowed sufficiently ahead of sowing to destroy volunteer seed of sorghum.

- Care should be taken to remove *Sorghum helepense* seed in the field and within the isolation distance.

Field Inspections

- A minimum of four field inspections should be made during the crop period:

First inspection:	During preflowering stage
Second and third inspections:	During flowering stage
Fourth inspection:	During preharvest stage

Field standards

The minimum field standards and acceptable seed standards are given in Tables 1-4.

Table 1. Minimum isolation distance required for foundation and certified seed of sorghum.

Field	Minimum isolation distance (m)	
	Foundation seed field	Certified seed field
Other grain sorghum fields	300	200
Field of same variety not conforming to varietal purity	300	25
Forage sorghum and Johnson grass	400	400

Table 2. Maximum permitted level of pollen shedders, off-types, and diseased heads for foundation and certified seed of sorghum.

	Maximum permitted level (%)	
	Foundation seed field	Certified seed field
Pollen shedders	0.05	0.1
Off-types in both seed parent and pollinator	0.01	0.05
Diseased heads like grain smut and head smut at final inspection	0.05	0.1

* However, reinspections are allowed after removal of diseased plants.

Table 3. Seed standards for foundation and certified seed of sorghum.

Seed standard	Foundation seed (%)	Certified seed (%)
Seed purity (minimum)	98	98
Inert matter (maximum)	2	2
Other crop seed (maximum)	0.05	0.1
Weed seed (maximum)	0.05	0.1
Germination (minimum)	80	80
Moisture (maximum)	12	12

Table 4. Screen sizes prescribed for cleaning of sorghum seeds.

Screen	Round	Slotted
Top screen	12/64" or 4.75 mm	--
Bottom screen	9/64" or 3.55 mm	1/12" x 1/2" or 2.1 mm

Pearl Millet

Eligibility Requirements for Certification

- An inbred line, to be eligible for certification, should be from a reliable source and approved by the certification agency.
- Hybrid seed should be the F_1 progeny of two approved inbred lines, one of which should be a male-sterile line.

Classes and Sources of Seed

- An inbred line should be a relatively true-breeding strain resulting from self-pollination and selection.
- Foundation seed should be the progeny of an approved male-sterile line and an approved restorer line (the male parent) for the purpose of producing hybrid seed.
- A male-sterile line should be a strain carrying cytoplasmic-genic male sterility.
- The certified seed class should be the hybrid seed that can be sown for any use except seed production.

Land Requirements

- The land to be used for hybrid seed production of pearl millet should be free of volunteer plants.

Field Inspection

- A minimum of four inspections should be made.
- The first inspection should be made before flowering, preferably within 30 days after sowing in order to check isolation, volunteer plants, outcrosses, sowing ratio, errors in sowing, incidence of downy mildew, and other relevant factors.
- The second and third inspections should be made during flowering to check pollen shedders, off-types, downy mildew/green ear, and other relevant factors.
- The fourth inspection should be made at maturity and prior to harvesting in order to detect the incidence of downy mildew/green ear, ergot, and smut, and to verify the true nature of the plant, and other relevant factors.

Field Standards

- Seed fields should be adequately isolated from other fields as listed in Table 5.

Table 5. General field standards for pearl millet seed production.

Field	Minimum distance (m)	
	Foundation seed field	Certified seed field
Fields of other varieties including commercial hybrids of the same variety	1000	200
Fields of the same hybrid (code designation) not conforming to varietal purity requirements for certification	1000	200
Fields of other hybrids having a common male parent and conforming to varietal purity requirements for certification	—	5
Fields of other hybrids having a common male parent but not conforming to varietal purity requirements for certification	—	200

- Seed fields should be free from any contaminants as listed in Table 6.

Table 6. Specific requirements for pearl millet seed production.

Factor	Maximum permitted (%)	
	Foundation seed	Certified seed
Off-types in seed parent at any one inspection at and after flowering	0.050	0.10
Off-types in pollinator at any one inspection at and after flowering	0.050	0.10
Pollen-shedding heads in seed parent at any one inspection at flowering	0.050	0.10
Plants infected by downy mildew/green ear disease at any one inspection	0.050	0.10
Ergot earheads parent at final inspection	0.020	0.040
Earheads infected by grain smut at final inspection	0.050	0.10

- Seed from such fields that have been reported to contain ergot infection— even within the prescribed limits—at field stage should be subjected to floatation treatment with brine to become eligible for certification.

- Seed fields with incidence of grain smut more than the maximum permissible level can, however, be certified if such seed is treated with an approved organo-mercurial fungicide not earlier than a month prior to its sowing.

Seed Processing

In the broadest sense, seed processing encompasses all the steps involved in the preparation of harvested seed for marketing, i.e., handling, shelling, preconditioning, drying, cleaning, size-grading, upgrading, treating, and packaging. Seed processing requires equipment and machinery, conveyers and structures which require mechanical skills and engineering principles.

A variety of contaminants must be removed from the raw seed such as inert matter and undersized seeds, which are not in themselves harmful but influence seed flow ability and plantability. Insect-infested seed contribute to storage problems, and weed and other crop seeds seriously affect crop production if they are not removed.

A variety of equipment is available for processing seed. It ranges from the simple, indigenous winnowing and sieving trays to the sophisticated electric sorting machines. Though differing in type and design, all processing machinery have one thing in common, i.e., separation of good seeds from ill-filled and undersized seeds and other undesirable material (inert matter). Depending on the quality, the seed requires to be processed in a definite sequence by several machines, each removing a certain type of unwanted material. The choice of machines for processing seed depends on the kind of seed being processed, the nature and kind of unwanted materials (weed seed, other crop seed, inert matter, etc.) in it, the quantity of each in the raw seed, and the quality standards that must be met. Thus, the processor must be as familiar with seed standards and seed characteristics as he is with the processing equipment.

Steps in Processing

Seed-processing operations can be divided into several definite steps that must be carried out in a specific sequence. The first step is receiving the seed. Seed arrive at the processing plant in bags or in bulk. From the receiving station, the seeds go into bulk storage to be held for later processing, or directly into the processing line for cleaning. The next step is conditioning and preclearing. This includes removal of appendages and large pieces of trash.

The first actual cleaning step is basic cleaning. The air-screen machine is the most common basic cleaner. It makes size separations and aspirates the seed. Often, it may be necessary to send the seed through one or more special separating or upgrading machines to remove a specific contaminant. These special machines separate crop and weed seed by differences in their specific physical characteristics. When all possible inert matter and weed or other crop seeds have been removed, the seeds are ready for bagging. A fungicide or insecticide treatment is applied before packing. The seeds may then be shipped to other places or held in storage.

Seed processing is based on differences in physical properties between the desirable seed and the contaminating seed. Seeds that do not differ in some physical characteristic cannot be separated.

If a difference exists between the seeds and a machine is available which can differentiate between them in a consistent manner, then they can be separated. Seed processors can choose from a wide selection of machines that differentiate between seeds differing in size, length, shape, weight, surface, texture, color, affinity for liquids or conductivity. A single machine cannot separate seeds that differ in all these characteristics. In most instances, a different machine must be used to make separations based on each of these characteristics.

Size. Size is the most common difference among seeds, and between seed and undesirable material. The air-screen machine enables grading of the seed into different sizes depending upon width and thickness by the use of a series of perforated shutters. One or more air-blast separations remove light material.

Length. Length differences are common between different crop seeds and weed seeds. Length separators are used by many processors to upgrade and improve the quality of seed. Both the indented cylinder and disc separator make length separations.

Shape. Shape varies widely among seeds. The separations made by the air-screen machine are often related to differences in shape, especially when triangular-hole screens are used. The indented cylinder and the disc separator take advantage of shape differences, particularly when they are a function of length. There is another machine, known as spiral separator, specially designed to separate round from flattened seeds.

Mass. Many seeds differ in mass, specific gravity or relative density per given unit of volume. Mass or specific gravity is the basis of the air-blast separations in an air-screen machine. However, the gravity separator, the stonier, the aspirator, and the pneumatic separator are all designed to make specific separations by differences in mass or specific gravity of seed.

Surface texture. The relative roughness or smoothness of the seed coat, i.e., surface texture, is a common difference between seeds. The roll or dodder mill, the draper belt, the magnetic separator, and the vibrator separator, all effect separation of seeds differing in surface texture.

Color. Many seeds differ in color or reflectivity. Electronic color sorters are used to make color separations in the larger crop seeds.

Affinity for liquids. Seeds also differ in their affinity for liquids, or the rate at which their surface will absorb liquids. The magnetic separator, separates the seeds on the basis of these differences.

Conductivity. Seeds also differ in their ability to hold or conduct an electrical charge. The machine which separates seed on the basis of electrical properties is called electrostatic separator, and consists essentially of a conveyor belt which carries a single layer of seed beneath an electrode.

Harvest and Postharvest Handling of Breeder Seed of Sorghum and Pearl Millet

C T Hash

Important stages in the process of safe and efficient movement of breeder seed from the breeder seed production field to the foundation seed producer include selection and harvest of panicles in the isolation plot, drying the panicles, threshing and cleaning the seed, further drying prior to storage, storage in bulk, packaging and dispatch to foundation seed producers, and record keeping. During all these stages, it is necessary to take precautions to continue to maintain the purity of the individual breeder seed stocks and prevent adulteration. Close supervision is necessary to ensure that the breeder seed that reaches the foundation seed producers is viable, vigorous, and contains only few contaminants.

Harvest

The harvest of panicles from a breeder seed production plot is the last but one opportunity that the breeder has to control the female parentage of the breeder seed-lot. Harvest is a far more appropriate stage for this than the last opportunity, i.e., evaluation of harvested panicles prior to threshing. Harvest should be undertaken as soon as possible after the crop reaches physiological maturity. Harvest after physiological maturity depends on the facilities available for postharvest drying of the panicles. If only sun-drying facilities are there, then it is better to delay harvesting a week or more after physiological maturity before harvesting in order to allow the sun and wind to reduce the moisture content of the seed.

Panicles should normally be harvested from the center of the breeder seed production plot. The amount of border to be leaft depends on the species and type of material being produced: One row for sorghum R-lines and open-pollinated cultivars, four rows or more for pearl millet open-pollinated varieties and A/B pairs of both species. Panicles selected for harvest should be standing plants that are typical of the line. The best plants and the worst plants should both be left in the field. Early plants of pearl millet are more likely to bear seed produced by pollen from outside the plot; so these too should not be harvested for seed. Late plants, extra-tall plants, and diseased plants should not be harvested. The harvested panicles should be collected in clean (preferably new) gunny bags, labelled inside and outside with the name of the material and the location where it was produced. Harvested panicles should be dried and stored prior to threshing. During drying and storage, care must be taken to keep panicles of different genotypes (e.g., an A-line and its B-line maintainer) in separate physical facilities to avoid inadvertent mixing.

Drying

The purpose of drying is to reduce the moisture content of the seed to facilitate threshing and cleaning, to maintain seed viability and vigor, and to reduce deterioration of the seed due to growth of molds, other microbes, and storage insects. A two-stage drying process is preferred. In the first stage, panicles are dried down to a moisture content of 15-20% where the seed is easily threshed free from the attached floral structures (lemma, palea, glumes, etc.). But the seed is still not dry enough, and hence, is easily damaged. After threshing and cleaning, the seed should be dried further—to a moisture content below 12%—to permit safe long-term storage. Drying offers the following advantages:

- Early harvest, which reduces the risk of crop loss or damage due to rains at maturity;

- Long-term storage of the seed;
- More efficient use of land and staff/labor;
- Use of stover as green fodder; and
- Production of better-quality seed.

Sun-drying and forced-air-drying are the two most commonly used methods. Sun-drying can be very effective in most sorghum and pearl millet production environments, but forced-air-drying is not as dependent on the weather.

Sun-Drying

For sun-drying, it is necessary to allow the standing crop to dry in the field for a week or more after physiological maturity. The panicles are then harvested and allowed to dry further for several days in the sun over dry soil or tarpaulins or, preferably, on a clean, dry, cemented threshing floor. The seed crop is then threshed and winnowed before being spread in a thin layer on the threshing floor to dry further. Stirring and turning the drying seed will speed up the process. Care must be taken to avoid damaging the seed, for it gets more brittle and fragile as its moisture content is reduced. During drying, one needs to take precautions against damage by storage insects, especially ants. The major advantage of sun-drying compared with forced-air-drying is that the former requires much less capital expenditure and limited operational expenses. The disadvantages are that it delays harvest, which increases the risk of weather damage to the standing crop. Since the harvested crop is dried outdoors, the risk of weather damage continues until the drying process is complete. Finally, compared with forced-air-drying, there is greater likelihood of physical admixtures when the seed is sun-dried. The following precautions must be taken with sun-drying:

- Use a clean, dry, cemented threshing floor;
- Only one crop variety, and produce from one plot, should be handled on one threshing floor at any one time.

Forced-Air-Drying

In this process, forced air passes through the damp seed and picks up the water. The evaporating moisture from the seed cools both the air and the seed. As the air cools, its water-holding capacity is reduced, and the cool, moist air must be carried away from the seed. Therefore, you need a continuous supply of warm, dry air to drive away the cool and moist air, and dry the seed. This air need not be heated in most sorghum and pearl millet seed production environments, although it may sometimes be necessary. Forced-air-drying will be most effective when the following factors are taken into consideration:

- Relative humidity: The ratio of the ambient vapor density to the saturation vapor density at air temperature;
- Moisture equilibrium between the seed and the air; and
- The temperature difference between the ambient air and heated air.

Forced-air-drying can rely on natural air-drying, or supplemental heat-drying in which air temperatures are raised 5-10°C to reduce the relative humidity and facilitate drying. When using natural air-drying, it is necessary to force fresh air through the drying seed during the warm, dry parts of the day. At night, temperatures normally fall near the dew point at which the saturation vapor density is 100%. Forcing air of 100% humidity through the seed may increase rather than decrease the moisture content. These methods will require 1-3 weeks to reduce the seed moisture content to a safe level (<12%). A drying temperature of 40°C is the maximum recommended for drying of sorghum and pearl millet breeder-seed and nucleus-seed stocks.

For commercial seed production, heated air drying is often used. In this method, air is heated to about 40°C above the ambient air temperature before being forced through the seed.

Threshing and Cleaning

Once the selected harvested panicles have been dried to a moisture content of about 12%, the seed can easily and safely be threshed. Various winnowing and cleaning operations can be undertaken to separate the seed from the chaff. Threshing and winnowing can be done manually or mechanically. If machines are used, they must be cleaned and inspected before threshing of each breeder seed-lot. Care must be taken not to thresh the seed when it is very dry as it is more easily injured. Similarly, care must be taken to use the minimum effective rotor speed of the thresher and to minimize the time that a given portion of the seed spends in the threshing chamber in order to minimize injury to the seed.

Cleaning is undertaken to separate undesirable materials from the seed. These undesirable materials can include:

- inert matter (e.g., dirt, stones, and chaff);
- weed seed,
- other crop seed,
- light and chaffy seed, and
- off-size, damaged, or deteriorated seed.

Seed cleaning is based on the physical properties of the seed and undesirable materials. Properties important for sorghum and pearl millet seed include:

- seed size (length, width, and thickness),
- density,
- shape, and
- surface texture.

For sorghum and pearl millet, cleaning operations can be divided into three groups:

- preconditioning/precleaning using a scalper to remove large inert matter,

- basic seed cleaning, using an air-screen cleaner, and
- upgrading, preferably using a gravity separator.

After threshing and cleaning, the seed should be dried further, down to a moisture content no greater than 12% to permit safe storage (Table 1).

Table 1. Moisture content of sorghum seed as a function of relative humidity.

Relative humidity (%)	15	45	75	100
Moisture (%)	6.4	10.5	15.2	21.9
	<-----Safe----->||<-----Not safe----->			

Storage

Breeder seed and nucleus seed of pearl millet and sorghum need to be stored in a cool, dry place. When no humidity control is possible in the cool place that is available, dry seed must be stored in hermetically sealed containers (e.g., new paint cans). A good seed-lot can be safely held for 20 years or more under such conditions. For places where humidity control is possible, Table 1 provides an indication of the moisture content of seed that equilibrates with the air in the store room. It is the relative humidity of the air in the store room, not outside, that is tabulated. Safe seed storage will require that relative humidity in the store room be maintained below 45%.

Place naphthalene balls at the rate of 20 g 10 kg^{-1} of breeder seed in the storage containers to serve as a deterrent to storage insects. If insects are already present in the seed-lot, this treatment will not eliminate them.

The seed-storage area must be kept clean to prevent breeding of insects, rodents, or fungi. Seed should be dried to a safe moisture level before being placed in the seed-storage area. Finally, it is only reasonable to store only high-quality seed in the seed-storage area.

Packaging

Breeder seed of sorghum and pearl millet should be packaged in small lots (1-10 kg, depending on the material). This seed can be packaged in advance in standardized units, or prepared from bulk upon receipt of the request from a seed-multiplication agency. It is important that the packaging be clean, moisture-proof, well-labelled, and not easily damaged in transit. The seed packet should have attached (preferably) or enclosed, a breeder-seed tag indicating the crop, label number, variety, quantity, seed-lot number, seed class, and actual data indicating inert matter, germination, and genetic purity, with a date for the germination test. In addition, the producing institution should be indicated, along with the signature of the breeder responsible for multiplication of the seed-lot.

Despatch and Planning

Despatch of the breeder seed in response to requests should be timely. This is possible only if breeder seed requirements are accurately forecast well in advance, and the different cultivars and hybrid parental lines are multiplied well in time. In India, seed-multiplication agencies indicate their likely requirements over a year in advance, and make a payment to the government based on the quantities required. Payment for the breeder seed itself is a separate matter. The government compiles the requests, and submits the totals to the institutions responsible for multiplying this breeder seed 8-10 months before the seed is actually required. This gives enough time to produce the required breeder seed.

Record Keeping

For each sample of breeder seed sent out to seed-multiplication agencies, it is necessary to maintain a record. At ICRISAT, a seed request number is assigned to each request received. This number is then included in all correspondence related to the request. A register of requests is maintained which includes information on the date the request was received, whom the seed was sent to, what materials were sent and in what quantities, when the seed was despatched, and how it was despatched. In addition, a breeder-seed register is maintained in which each despatch of breeder seed is recorded, in serial order of the breeder-seed tag. A cover letter is sent separately, indicating what material was sent, breeder-seed tag number and breeder-seed quantities, and requesting feedback on the utility of the material. Finally, the cover letter is accompanied by a breeder-seed certificate, in the format required by the state in which the foundation seed will be multiplied. Samples of breeder-seed tag and seed record are given in Figure 1 and Figure 2.

Crop—Pearl Millet (Bajra) Label No. 6539
Variety: ICTP 8203 Qty.: 2 kg Lot No. BS 193-5
Class of Seed—Breeders Seed

Date of Test: Siqnature

* Pure Seed 99.8% * Germination 95%

* Inert matter 0.2% * Genetic Purity 100%

• Based on actuals

Producing Institution:
International Crops Research Institute for the
Semi-Arid Tropics
Patancheru 502 324,
A.P., India.

Figure 1. A sample of a breeder seed tag.

Sl No.	Page Number of File	Seeds Indented	Seed	Supplied	Plant Quarantine		Name & Address	Date of Despatch	Remarks
			Pedigree	ICRISAT Number	Date Sent	Date Returned			

Figure 2. A sample of the seed request/seed despatch register.

Purity Test of Hybrids, Parental Lines, and Open-Pollinated Varieties of Sorghum and Pearl Millet

V Jaya Mohan Rao

Purity of seed is a very important criterion for the acceptance of a variety. This is ensured through various administrative and technical methods involved in seed production.

Classes of Seed

Since the introduction of hybrids of sorghum and pearl millet, there have been significant advances in the technology of seed production and processing. In sorghum and pearl millet, seed-production programs are mostly based on hybrids.

It is necessary to have a clear idea about the seed multiplication process before planning the production of large quantities of certified seed. Certified seed is produced in stages from the breeder seed. The originating breeder supplies the breeder seed to different institutions such as agricultural universities, central and state research institutions, and other recognized/sponsored organizations.

Breeder seed can also be produced by sponsored breeders. In special cases and in selected crops, permission may also be given to organizations such as the National Seeds Corporation (NSC), the State Seeds Development Corporations, and National or State Seed Farms which possess big farms, processing plants, storage facilities, and qualified personnel.

The breeder seed required for national varieties in India is arranged through the Department of Agriculture and the National Seeds Corporation of the Central Government. The breeder seed for state varieties can be produced by breeders of the states concerned. Breeder-seed plots are monitored by a team consisting of breeders, representatives of the state seed certification agency (SSCA), and the seed-producing agency. A set of five proforma are required to be filled by the breeder undertaking breeder seed production. They are called 'Breeder-Seed Production Proforma' (BSP).

- BSP-1: Allocation of breeder seed production by the crop-improvement project;
- BSP-2: Timetable of production and availability of breeder seed;
- BSP-3: Inspection report of the monitoring team;
- BSP-4: Breeder seed final production statement; and
- BSP-5: Breeder seed history sheet.

After receiving the five proforma, the Seeds Division of the Department of Agriculture of the Central Government estimates the total production of breeder seed for each crop and variety. Each state is required to submit its indent stating the requirement of breeder seed in that state, 18 months in advance. Based on these indents and the final production figures, the Seeds Division allocates the quantity of breeder seed to be supplied to each state, and indicates the place of availability and the dates by which to take delivery. The breeder seed comes with a golden yellow tag. The state governments in turn reallocate the breeder seed to the different indenters in the state (private and public sector

organizations).

Foundation seed is produced under the supervision of the SSCA on the farms of agricultural universities, state governments, corporations, and in farmers' fields. The SSCA examines the source of the breeder seed, and inspects the seed plots three or four times during the crop season. After the crop is harvested, the nonprocessed seed is sealed by the SSCA and sent to the processing plants. From the processed seed, the SSCA draws samples and sends them to the notified seed-testing laboratories (STLs) for testing of physical purity, germination, etc. The samples are also subjected to a grow-out test, to determine genetic purity. Seed of varieties and parents of hybrids are put through this test. The seed-lots which meet the certification standards are given the foundation-seed tags (white tags).

The procedure for production of certified seed is almost the same as for foundation seed. However, the grow-out test for genetic purity is conducted only in select crops like hybrid cotton, hybrid castor, and doubtful lots of other crops. The lots that meet the minimum seed certification standards are passed by the SSCAs and certified-seed tags (blue tags) are issued.

A model of the seed-multiplication chain is given in Figure 1. It is essential that every individual involved in seed production is familiar with the seed-multiplication chain based on the multiplication ratios (Table 1) to be able to plan for the production of certified seed. Defective planning may result in deficit or surplus production, both of which are harmful to the seed industry.

Table 1. Seed multiplication ratio (MR) of ICRISAT's mandate crops.

Crop	Seed rate (kg ha^{-1})	Multiplication ratio
Sorghum	12	1:100
Pearl millet	4	1:200
Pigeonpea	20	1:100
Chickpea	75	1:10
Groundnut	100	1:8
Finger millet	5	1:80

The system of variety/hybrid development and release in public and private sector organizations is different. Development procedures are as per breeding principles, whereas the release system is linearly adopted by public organizations only.

Field and Laboratory Tests

The seed-certification scheme, controlled pedigree systems, and rules and regulations for seed growing and distribution are all aimed at maintaining cultivar trueness and purity of seed. In spite of this, possibilities always exist for contamination of the original seed-lots by unwanted seeds of other cultivars or other types.

Causes of Contamination

Contamination can occur due to several factors.

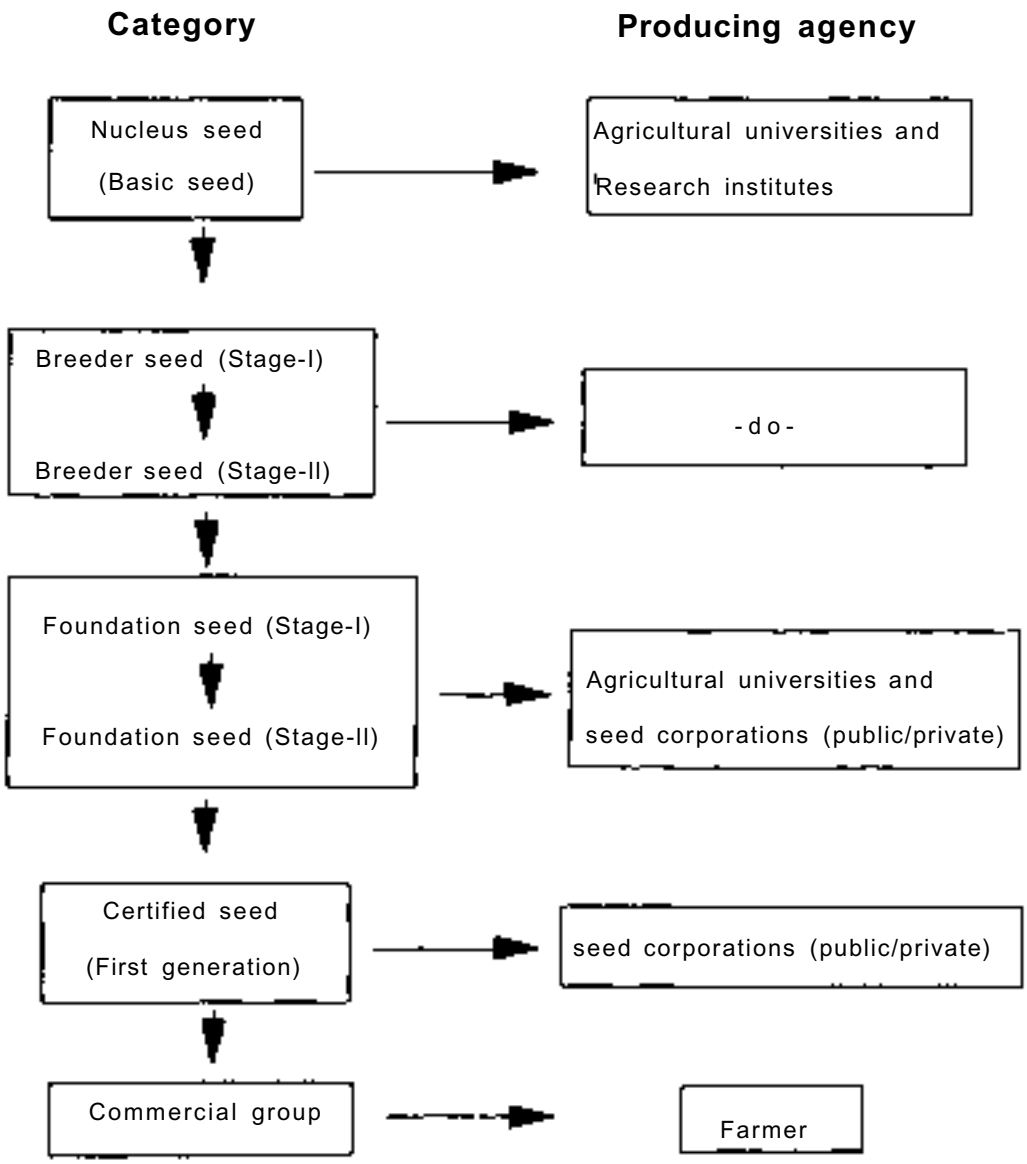


Figure 1. Seed-multiplication chain

The total number of generations after breeder seed and before the commercial crop should not exceed three. Production of Breeder seed (stage-II) should be taken up only in the case of acute shortage.

- Natural crossing with another cultivar, especially in open-pollinated crops
- Mutation
- Unclean harvesting equipment
- Carelessness at processing plant
- Mistakes in bagging and tagging

To detect and control such contamination, pre- and postharvest control tests are conducted by means of cultivar identification/purity determination. Intensive crop-improvement programs have resulted in the development of a large number of varieties in all important crop species, including sorghum and pearl millet. Variety identification has therefore attained critical importance in national and international seed programs.

Different cultivars are commonly identified on the basis of morphological differences in seed, seedling, and mature plant. The Distinctness, Uniformity, and Stability (DUS) test or testing a cultivar for these characters is an essential step for the registration of a variety.

Distinguishing varieties on the basis of seed morphology is not always possible. But it is undoubtedly one of the most commonly used criterion. Cultivar-identification techniques to assess purity are essential for commercial seed production and certification. Conventionally, such identification has been accomplished through the grow-out test. In practice, this is an extremely successful procedure, but it can be time-consuming, requiring large areas of land. Also, many of the morphological descriptors used are multigenic and quantitative, displaying continuous variation, whose expression is altered by environmental factors. Thus, there is a need to develop alternative tests which can distinguish varieties on the basis of stable biochemical properties of seed or seedlings.

An authentic standard sample must be available for comparison which is required to be treated and examined in the same way as the sample under test. In other words, seedlings and plants are compared at the same stage of development. A combination of laboratory and field methods may be used to determine the cultivar trueness and genetic purity of the sample. The laboratory methods used for the examination of morphology, seed characters, color reaction to certain chemical treatments, properties of seedlings, response of seedlings to controlled environmental factors, and growth stimulants are used to determine cultivar trueness. Of the various techniques available, analysis of seed and seedling proteins and isoenzymes using electrophoresis techniques are the most widely used because of their reliability, rapidity, and cost-efficiency.

To ascertain the genetic purity of the certified/truthfully-labelled seed, development of quick laboratory tests for key diagnostic characters has great value for the ever-expanding seed industry. These developments will go a long way in maintaining high seed standards and will benefit both seed producers and farmers.

Methods of Genetic Purity Assessment

Examination of Seed in the Laboratory

This test is accomplished by means of other distinctive variety (ODV) test in the laboratory. The test is on the basis of the texture, color, and shape of the seed in comparison with an authentic sample. The examples of seed color and shapes in pearl millet are listed in Tables 2a and 2b.

Table 2a. Seed color in pearl millet.

	Genotype	
Seed color	Hybrids	Hybrid parents
Brown	HHB 50, HHB 60	H77/833-2, H90/4-5
Brownish gray	HHB51, HHB 67, HHB 68, HHB 69	ICMP 451, D23
Gray	-	842A,841A and 841B
Light brown	ICMH 423	ICMP451, 843A, 843B, ICMP 423

Table 2b. Seed shape in pearl millet.

	Genotype	
Seed shape	Hybrids	Hybrid parents
Pyriform	H77/833-2, HHB 60	841A, 841B, H 90/4-5
Obovate	HHB 60, HHB 68, HHB 67	81A, 81B, ICMP 451, D23
Globular	ICMH 451, ICMH 423	842A, 842B, 843A, 843B, ICMP 432

Chemical Treatment of Seedlings

Characters of seedlings which may be produced in a relatively short time under laboratory conditions are sometimes used in cultivar testing. It is important that seedlings are grown under controlled conditions and that a control sample is grown simultaneously for comparison.

Phenol Reaction Test

To study the phenol color reaction (Table 3) the seeds are soaked in a solution of $CuSo_4$ at 1 and 2% and in a solution of Na_2Co_3 at 0.1% and 0.2% prior to test. Then the seeds are soaked in 1% phenol. The reaction is recorded after incubating the samples at 30°C for 24 h. Reaction to phenol with 0.2% Na_2Co_3 presoaking is better as compared to other treatments.

Table 3. Phenol color reactions of various pearl millet genotypes.

	Genotype	
Seed color	Hybrids	Hybrid parents
Black (+++)	HHB 61, HHB 69	H 77/833-2
Dark brown (+++)	HHB 67, HHB 68	D 23, IMMP 451
Brown (++)	HHB 50, IMCH 423	81A, 81B, H 90/4-5, ICMP 423, ICMP 451
No reaction (-)	-	842A, 842B, 843A, 843B, 841A

+++=High, ++=Medium, and +=Light reactions.

Shoot, Root, and Seedling Growth Response to Added Chemicals in Sorghum

To study the effect of DDT, BHC, Folidol, thiram, captan, 200 randomly selected seeds (25 seeds each in 8 replications) are treated with the powder in a manner that a layer of the chemical is visible on the seed coat. The seeds are then placed on two layers of moistened germination paper towels. They are covered with another moistened paper towel and rolled up. At the end of the seventh day, the rolled towels are taken out from the germinator and the shoot, root, and seedling length are compared with the control. A similar test can be done by using gibberellic acid (GA_3) and polyethylene glycol (PEG).

Electrophoresis

In common usage, electrophoresis refers to the movement of ions through a medium, whether in free solution, as in moving-boundary electrophoresis or when a supporting medium such as starch gel, polyacrylamide gel, cellulose, acetate or paper is employed.

Employing this principle, separation of proteins by electrophoresis is utilized for variety identification.

Field Plot Test

The possibility of proving the genuineness of a cultivar by the field plot test is based on the hereditary characteristics of the plants. Usually, cultivar differences are more distinct if the growth conditions are

favorable. The crop should be so grown that genetic differences express themselves as clearly as possible. It is essential to sow the various samples of the sample cultivar in succession and to sow standard samples at suitable intervals, e.g., one standard sample for every 10 samples to be tested. The design of a field plot is given in Table 4.

Table 4. Suggested design of a field plot to determine cultivar purity in sorghum and pearl millet.

Crop	Row length (cm)	Plant-to-plant spacing	Spacing between rows (cm)	Spacing between plots (cm)	Replications
Sorghum	6	10	60	90	2
Pearl millet	6	10	45	100	2

For assessing genetic purity, a minimum of 400 plants are required. The test is terminated after expression of the distinct character of a particular cultivar. The duration of the test depends upon the crop/variety. The variety is identified on the basis of diagnostic characters.

Genetic Purity Requirements

The genetic purity requirements for various classes of sorghum seed are given in Table 5.

Table 5. Genetic purity required for different classes of sorghum seed.

Seed class	Genetic purity (%)
Foundation seed	99.0
Certified seed	
Varieties	98.0
Hybrids	95.0

Diagnostic Characters for Pearl Millet

Leaf blade	Hairy/nonhairy
Leaf sheath	Hairy/nonhairy/pubescent/nonpubescent
Midrib color	White/dull white
Stem characters	Nodal hair predominant/absent, violet or green nodal pigmentation
Spike characters	Spike exertion negative/zero/positive
Spike shape	Conical/cylindrical/candle or oblanceolate/lanceolate

Bristling	Present/absent

Certification Procedures

The generally accepted system of seed certification involves field inspections, sample testing, and enforcement of minimum standards, which constitute the mechanism of seed quality control. The farmer is assured of a rich harvest if he uses certified seeds. The following definition of the term "seed certification" will be helpful in understanding the principles involved in the process.

Seed certification is a scientific and systematically designed process to secure, maintain, multiply, and make available seeds of superior crop plant varieties to farmers, to ensure:

- the genetic identity of a variety with respect to its distinguishable, uniform, and stability parameters;
- a high degree of physical purity;
- a high standard of seed health and germinability to produce vigorous seedlings and good plant stand; and
- freedom from all designated seedborne diseases, weeds, and other crop seeds ascertainable under field and laboratory conditions.

Phases of Seed Certification

- Application for certification
- Establishing a seed source
- Field inspection to verify conformity to field standards
- Postharvest supervision
- Grant of certificate and tagging

Maintenance of purity/quality at every stage of seed production is essential. Any flaw at any stage results in failure to deliver good-quality seeds, resulting in wastage of energy and money.

Development of Sorghum and Pearl Millet Seed Industry in India

G Harinarayana

The seed industry in India owes its development to several factors: The evolution of high-yielding varieties and hybrids, the role of seed as a vital and critical component of production, the ability of seed to support a productive agricultural system, the dependence on seed for sustaining agricultural productivity and production, and the ever-increasing demand for good-quality seed have prompted the development of a full-fledged seed industry comprising seed production, processing, certification, storage, and marketing.

Development of the Indian Seed Industry

The beginning of sorghum and pearl millet seed production and distribution can be traced to the second decade of the 20th century. The history of the sorghum and pearl millet seed industry is intertwined with the birth and growth of the Indian seed industry in general. Therefore, to recapitulate the history in chronological order it is presented here as Pre-Independence (1900-1946), Early Post-Independence (1947-1959), and Post-Independence (1960-1995) eras. The important milestones in the history of the sorghum and pearl millet seed industry are the establishment of the All-India Coordinated Project on Sorghum Improvement in 1960, the All-India Coordinated Pearl Millet Improvement Project in 1965, the establishment of the National Seeds Corporation in 1963, and the establishment of a private seed company, the Maharashtra Hybrid Seed Company (MAHYCO) in 1964.

Pre-Independence Era (1900-1946)

1922 Establishment of seed-multiplication laboratories by the Department of Agriculture of the United Provinces (now divided into Uttar Pradesh and Madhya Pradesh). These laboratories used to multiply and supply seed to big landlords for further multiplication. Loans were given for establishing chains of seed stores in each taluk (part of a district).

1925 The Royal Commission on Agriculture examined the introduction, spread, and distribution of seed of improved varieties in India. Following its suggestions, several state governments established research institutes.

1928 The Department of Agriculture started distribution of seeds of improved varieties. These seeds were either multiplied at one location and distributed over large areas or multiplied by a large number of farmers for their own use and/or distribution.

1944 The Famine Enquiry Commission and Foodgrains Policy Committee observed that crop botanists should evolve new varieties, test them, and hold on-farm demonstrations. Initially, multiplication of new varieties started on the farms of registered seed growers. Such seeds were procured at premium prices and distributed at concessional rates.

1945 Private vegetable seed companies started producing seeds of temperate vegetables in Quetta (now in Pakistan) and Kashmir.

1946 The All-India Seed Growers Merchants and Nurserymen's Association was formed to promote development of the vegetable seed industry.

Early Post-Independence Era (1947-1959)

1951 India's first Five-Year Plan (1951-1956) emphasized the need to develop a seed production and distribution program of improved seeds based on the food production forecast.

1952 The Grow More Food Enquiry Committee noted that seed of required purity was not available. An Expert Standing Committee constituted by the Indian Council of Agricultural Research (ICAR) formulated a concrete scheme for seed multiplication and distribution.

1956 During the Second Five-Year Plan period (1956-1961), a program for multiplication of nucleus seed into foundation seed was started at seed farms, and seed stores were established in each National Extension Service block. Plans for setting up seed-testing laboratories and cooperative stores were drawn up.

1957 The All-India Coordinated Maize Improvement Project was established in collaboration with the Rockefeller Foundation. This was a turning point in Indian agriculture, leading to the formation of a series of All-India Coordinated Crop Improvement Projects.

1959 The first Indo-American Agricultural Production Team recommended the establishment of a private seed industry. The team suggested that village-, block-, and district-level extension workers should be made primarily responsible for educating farmers on the use of improved seed. The state departments of agriculture are made responsible for seed certification, and private growers for seed supply (Agrawal 1980). The team further recommended setting up of state seed-testing laboratories, and development of uniform seed certification standards and seed laws. A committee of technical experts developed plans for a sound seed program for India. They also formulated a model seed law which formed the basis of subsequent seed laws.

Post-Independence Era (1960-1995)

1960 The second Indo-American Agricultural Production Team endorsed the first team's recommendations, and emphasized the need to accelerate their implementation.

The Program Evaluation Committee felt that the norms for setting up 10-ha seed farms were not strictly followed by the states. It also pointed out that seed farms were being run by nonqualified personnel, and that precautions necessary for maintenance of purity of seeds were not taken. It also said that the seeds produced by registered growers were not being used.

1961 The Seed-Multiplication Review Team made significant recommendations regarding production and distribution of all important agricultural crops over a period of five years. This included varieties of millets, oilseeds, and pulses, and production of breeder seed under the supervision of crop specialists. It recommended proper distribution of registered seed, and prescribed standards for purity, germination, field and seed inspections, harvesting, drying, storage, and seed treatment.

The first four maize hybrids were released by the All-India Coordinated Maize Improvement Project.

1962 The Government of India constituted a committee to formulate the Seeds Act.

1963 The National Seeds Corporation (NSC) (formerly the Central Seeds Corporation) was established to initiate foundation and certified seed programs, encourage production and marketing of seeds, assist in the development of seed certification programs, seed law and seed-law enforcement programs, train personnel in seed programs, and coordinate the improved seed programs. This was the beginning of the development of a strong seed industry based on scientific principles.

1964 The first seed company in the private sector, the Maharashtra Hybrid Seed Company Limited (MAHYCO) was established. This company started a research program in 1966.

The Crop Improvement and Certified Seed Producers Association was formed with active support from the Rockefeller Foundation and the Government of India.

Seed-testing laboratories were started.

1965 The National Seeds Corporation organized the first Seed-improvement training course.

1966 A High-Yielding Varieties Program (HYVP) was envisaged in India, covering an area of 9.2 m ha in 1968-69, and 25 m ha in 1973-74 with rice, wheat, sorghum, pearl millet, and maize. This encouraged strong linkages among NSC, the state departments of agriculture, and private entrepreneurs.

The Seeds Act was passed to regulate production and supply of quality seed. The law was later amended in 1972. This law had a provision for voluntary certification of seeds, but compulsory truthful labelling. The minimum standards for seed to be sold were fixed. The Seed Certification Act came into being officially.

1968 Seed Rules were framed. They were amended in 1973, 1974, and 1981.

The State Review Team made 101 recommendations relating to registration and release of varieties, seed production, processing, storage, quality control, and marketing. The recommendations covered training, the role of various agencies, finance, and credit. The NSC was to continue producing foundation seed till the agricultural universities took over the function under the coordination of a central agency. The state governments were to set up their own seed certification agencies. The cooperative and private sectors were to be encouraged to replace governmental agencies in seed production, processing, and marketing. Procurement and sale prices were to be regulated by market forces.

1969 The Terai Development Corporation (TDC) Limited was established during the fourth Five-Year Plan (1969-1974) with assistance from the World Bank. The primary objective of TDC was to produce one-third of the quality seed requirement envisaged by the fourth Five-Year Plan, and thereby to promote the development of the Terai area of Uttar Pradesh.

The Farms Corporation of India was established with a view to accelerating foundation seed programs.

1971 The Indian Society of Seed Technology was formed to provide its members a forum to share their seed production experience. This society also brought out two publications, Seed Research and Seed Technology News. Minimum seed certification standards were formulated.

The National Commission on Agriculture in its interim seed review called for maintaining the highest standards of seed purity.

1973 The first postgraduate course in seed technology was started at the Indian Agricultural Research Institute (IARI), New Delhi.

1975 The National Seed Project (NSP) was initiated to reorganize and expand the seed industry. It developed a broad-based network of seed production agencies in collaboration with the NSC as principal coordinator for seed testing, seed certification, seed storage, and marketing. Public as well as private agencies were to be involved in breeder, foundation, and certified seed production.

1976 The National Commission on Agriculture in its final report recommended that the seed industry should be commercialized. It also recommended that compact productive areas should be identified for seed production. It said seed processing must be made compulsory and the grow-out test should be made an integral part of the certification of parental material. The commission wanted storage conditions for nucleus, breeder, foundation, and certified seeds improved. It wanted incentives to be provided for marketing. It felt that seed-technology research and education ought to receive attention and that the Seeds Act must be implemented rigorously.

Seed corporations were established in four states: Andhra Pradesh, Haryana, Maharashtra, and Punjab under NSP Phase I.

1978 A buffer stock of seeds was initiated to meet the requirements of seeds in case of natural calamities and to bridge shortfalls in production by state seed corporations. Subsequently, the Government of India supported buffer-stock seed production from 1987.

During NSP Phase II, the states of Bihar, Karnataka, Orissa, Rajasthan, and Uttar Pradesh established state seed corporations.

1979 The All-India Coordinated Project on Seed Technology Research was initiated with 14 centers.

1980 The Government of Maharashtra decided to supply breeder seed to private seed companies for producing their own foundation seed for improving the overall quality of seed. This was subsequently endorsed by the Government of India in 1983.

1982 The Indo-Danish Project on Seed Technology Research and Training came into operation.

1983 The Seeds Act was legislated to bring seed under the Essential Commodities Act.

1985 During the seventh Five-Year Plan period (1985-90), public and private sector companies were strengthened for distributing certified/quality seeds. In addition to agricultural universities and the Indian Council of Agricultural Research (ICAR), NSC, and the State Farms Corporation of India (SFCI) were asked to produce breeder seed. Private seed producers were allowed to produce foundation seed. Seed-testing laboratories, seed certification agencies, seed-law enforcement, seed-technological research and training facilities were strengthened.

The Seed Association of India (SAI) was established to provide a platform for seedsmen to exchange views, ideas, and information.

1987 The Expert Group on Seeds examined the whole gamut of the seed sector, such as production, quality control, and marketing.

1988 A seed section was established at ICAR headquarters to deal with all aspects of seed.

The Central Seed Testing Laboratory was established at IARI, New Delhi, to discharge statutory functions.

The Minimum Seed Certification Standards were modified and revised as the Indian Minimum Seed Certification Standards published by the Central Seed Certification Board.

A new seed policy for import of improved varieties/hybrids of coarse cereals, pulses, oilseeds, and fodder was announced. Vegetable and flower seeds were placed under the Open General Licence.

1989 A Center for Excellence in Seed Technology was established at the Haryana Agricultural University, Hisar, with the financial assistance of the United Nations Development Program (UNDP).

The Expert Group on Seeds suggested to the Government of India that in-service training be provided to seed inspectors. They may be made exclusively responsible for seed quality control and that targets be fixed for seed testing.

1990 The National Seeds Project III envisaged strengthening of the All-India Coordinated Research Projects. It wanted breeder seed production units to be located in agricultural universities. It recommended that governmental agencies should be involved in quality control of seeds and that the private sector should be in the seed business.

1994 The Government of India's Working Group on Seeds estimated the seed requirement for the year 1994-95 at 0.86 million tons compared to the 1.28 million tons that would be required by 2000 A.D.

Sorghum and Pearl Millet Seed Industry

1960 The Accelerated Sorghum and Pearl Millet Improvement Project was established in collaboration with the Rockefeller Foundation. A large number of germplasm collections were assembled from India and abroad, which later were transferred to the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT).

1963 The NSC shouldered the responsibility of foundation and certified seed production, certification, and marketing. It developed field and seed standards.

1964 MAHYCO began sorghum and pearl millet seed production.

The first grain sorghum hybrid, Coordinated Sorghum Hybrid 1 (CSH 1) was released for commercial production in India. This was followed by the release of 13 more hybrids (CSH 2 to CSH 14) until 1995.

1965 The first pearl millet grain hybrid, Hybrid Bajra 1 (HB 1), was released in India. This was followed by hybrids HB 2 to HB 7, BJ 104, CJ 104, ICMH 451, MH 182, HHB 67, Pusa 23, and many others in the private sector in due course. HB 1 certified seed production was initiated in Karimnagar and Ranga Reddy districts of Andhra Pradesh in 1965. Large-scale seed production of HB 1 was undertaken in Nizamabad district and on a limited scale in Warangal district. In 1995, Nizamabad had nearly 12 000 ha under hybrid pearl millet, the highest in India followed by 6000 ha in Gujarat (Panchmahal and Vadodara districts). The dry climate of Nizamabad promotes development of bold, lustrous and disease-free seed.

The Accelerated Sorghum and Pearl Millet Improvement Project was bifurcated into the All India Coordinated Sorghum Improvement Project (AICSIP) and the All India Coordinated Millets Improvement Project (AICMIP).

The Telangana Cooperative Hybrid Seeds Society was established to produce maize, sorghum, and pearl millet hybrids with the help of the United States Agency for International Development (USAID).

1967 Production of CSH 1 seed was started in Kurnool, Andhra Pradesh. This district still produces hybrid seeds of sorghum on a large scale.

1972 Two more districts, Nellore and Chittoor, started CSH 1 production.

1973 West Godavari district in Andhra Pradesh started production of CSH 5 and CSH 6, but had to discontinue it due to the problem of discoloration of seed.

1978 The production of CSH 5 and CSH 9 was started in Nandyal in Kurnool district, which proved to be the most ideal niche for sorghum hybrid seed production in India. It continues to be so even today.

1982 MAHYCO-bred pearl millet hybrid MBH 110 was released by the Central Variety Release Committee.

Khammam district in Andhra Pradesh started pearl millet hybrid seed production.

1986 In Guntur district in Andhra Pradesh, production of hybrid pearl millet failed due to high incidence of downy mildew. Similarly, seed production of HB 1 in 1967 and BJ 104 in 1978 failed in Nellore, due to downy mildew disease.

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Annexure I

List of participants who attended the training course on 'Maintenance of male-sterile lines and open-pollinated varieties of sorghum and pearl millet and their use in seed multiplication'

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About ICRISAT

The semi-arid tropics (SAT) encompasses parts of 48 developing countries including most of India, parts of southeast Asia, a swathe across sub-Saharan Africa, much of southern and eastern Africa, and parts of Latin America. Many of these countries are among the poorest in the world. Approximately one-sixth of the world's population lives in the SAT, which is typified by unpredictable weather, limited and erratic rainfall, and nutrient-poor soils.

ICRISAT's mandate crops are sorghum, pearl millet, finger millet, chickpea, pigeonpea, and groundnut; these six crops are vital to life for the ever-increasing populations of the semi-arid tropics. ICRISAT's mission is to conduct research which can lead to enhanced sustainable production of these crops and to improved management of the limited natural resources of the SAT. ICRISAT communicates information on technologies as they are developed through workshops, networks, training, library services, and publishing.

ICRISAT was established in 1972. It is one of 16 nonprofit, research and training centers funded through the Consultative Group on International Agricultural Research (CGIAR). The CGIAR is an informal association of approximately 50 public and private sector donors; it is co-sponsored by the Food and Agriculture Organization of the United Nations (FAO), the United Nations Development Programme (UNDP), the United Nations Environment Programme (UNEP), and the World Bank.

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