Sorghum and Millets: Chemistry and Technology

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FAO-IGG. 1988. Sorghum 1988: The Structure and Characteristics of the World Sorghum Economy. Working pap. Committee on Commodity Problems, Intergovernmental Group on Grains, 23rd session. FAO, Rome.

FAO-IGG. 1990. Millet 1990: The Structure and Characteristics of the World Millet Economy. Working pap. Committee on Commodity Problems, Intergovernmental Group on Grains, 24th session. FAO, Rome, 1990.

RACHIE, K. O. 1975. The Millets: Importance and Utilisation and Outlook. Int. Crops Res. Inst. Semi-Arid Tropics (ICRISAT), Patancheru, A. P., India.

SEETHARAM, A., RILEY, K. W., and HARINARAYANA, G. 1989. Small millets in global agriculture. Proc. Small Millets Workshop, 1st, Bangalore, 1986. Oxford and IBH Publ. Co., New Delhi.

WIETGREFE, G. W. 1989. Proso Millet: A Trade Summary. Author's publication, Pierre, SD.

CHAPTER 3

AGRONOMIC PRINCIPLES

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INTRODUCTION

Sorghum and the millets are annual grasses that are extensively used in tropical areas of the world and have moved significantly into temperate regions. In tropical areas, these crops are wholly utilized, as they are often used for food, feed, building material, and fuel. The more important millets include pearl, finger, foxtail, and proso millets. There are other millets of more local significance, including teff, kodo, barnyard, fonio, and little millet. These crops have different areas of adaptation, growing periods, and grain characteristics. As a broad generalization, sorghum and millets are primarily used for food and beverage in tropical areas and as feed in temperate areas. Information on nutritional and quality characteristics is greatest for sorghum, less for pearl millet, and little to nonexistent for other millets. Both grain and stover traits have been studied, and in terms of genetic control and the influence of environmental factors, the greatest information is available for protein and amino acids and nutritional inhibitors, with little information available for carbohydrates and other constituents.

Germ Plasm Resources

Sorghum and millet breeders in a number of countries where these crops are important began collections of the cultivars and wild types growing in their countries some 50–70 years ago. Collections were developed for sorghum, pearl and finger millets, and foxtail, proso, barnyard, and small millets. During the mid-1960s, as part of the Indian Agricultural Program of The Rockefeller Foundation, with support from the U.S. National Academy of Sciences, existing collections were brought together, and cultivars growing in India were systematically collected.

These collections became the responsibility of the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) and continued to expand. Accessions with ICRISAT are presented in Table 1.

These collections provided a genetic base used by many breeders to diversify their breeding stock. Texas A&M University and the U.S. Department of Agriculture initiated a program to convert useful tropical sorghum cultivars to temperate adaptation. These converted cultivars have been widely used in sorghum improvement programs in both the temperate and tropical zones.

The collections also made it possible to breed for resistance to biotic and abiotic stresses (drought resistance being of particular interest). Variation in the sorghum collection increased the opportunity to breed for end use. The first effort was to match as closely as possible local preferences for foods and beverages made from sorghum, and to a somewhat lesser extent, from pearl and finger millets. Interest expanded into the preparation of specialty foods and to blending the flour of sorghum and pearl millet with that of other cereals (wheat and maize) and legumes.

Following the discovery of high lysine in maize, interest in nutritional quality grew and led to the discovery of high lysine in sorghum and to the antinutritional effect of high tannin. Traditional uses and techniques were documented, and these traits were extensively studied in a number of laboratories.

The study and use of resistance traits, nutritional characteristics, and quality of food, feed, and beverages has contributed to the development of a diverse array of useful breeding stock important to the strengthening of most sorghum and millet improvement programs around the world. A number of these traits are considered in this chapter.

The Structure of the Seed

The structures of sorghum and millet grains have much in common. A detailed discussion of the structure of the sorghum grain is presented by Rooney and Miller (1982). The major components of the seed are the pericarp or outer cover, the endosperm or storage organ, and the embryo, which germinates to reproduce a plant. There are four components of the pericarp; the outer layer is divided into the epidermis (frequently pigmented) and the hypodermis. The middle portion of the pericarp, the mesocarp, may vary from thin and translucent to thick, giving the pericarp a dull "chalky" appearance. The endocarp is the innermost layer of the pericarp, composed of narrow, long cells, and is the point of separation of the pericarp from the rest of the seed during the milling process.

The testa, which may or may not be present, is the layer between the pericarp and the endosperm. This is the tannin-containing layer, and therefore important to the nutritional characteristic of the grain.

TABLE 1
Sorghum and Millet Collections of ICRISAT

Crop	No. of Accessions
Sorghum[a]	33,108
Millets	
Pearl[a]	22,059
Finger[b]	3,220
Foxtail[b]	1,452
Proso[b]	831
Little[b]	423
Barnyard[b]	612
Kodo[b]	544

[a] Data from ICRISAT (1992).
[b] Data from Prasada Rao et al (1993).

The endosperm forms the bulk of the kernel, generally being corneous on the outer extremes and floury toward the center. Starch granules in the corneous outer portion are embedded in a protein matrix and are difficult to separate. Protein content in the floury endosperm is less than in the corneous types, and there can be voids in the structure contributing to a more opaque appearance of this portion of the endosperm. Starch is more easily recovered from the floury endosperm (Rooney and Miller, 1982).

The embryo appears at the lower portion on one side of the seed. Most of the oil content of the seed is in the embryo.

GENETICS OF SORGHUM GRAIN CHARACTERISTICS

Protein

Sorghum protein has several components based on solubility fractions. Of greater concern is the alcohol-soluble prolamin. Prolamin can be divided into fractions: fraction III (based on the Landry-Moureau fractionation) is highly crossbonded and referred to as kafirin. It is this fraction that has a negative impact on sorghum protein quality. Fraction II is nutritionally better. Maize and pearl millet have some four to six times more fraction II than III, while sorghum has twice as much fraction III as fraction II (Doggett, 1988).

Nitrogen (N) is an important plant nutrient having significant impact on yield and nutritional quality of the grain. Varieties differ in the uptake and transport of nitrogen as well as its impact on plant performance.

Nitrogen uptake per plant and nitrogen transfer efficiency varied in one experiment, ranging from 0.22 to 1.14 g of N/plant and transfer efficiency from 57.8 to 86.6% at a given total N. A weak negative N content versus grain yield correlation was identified. A high positive correlation was observed between high nitrogen transfer efficiency and high harvest index (weight of grain as a proportion of total dry matter). Grain yield was positively correlated with total N in the plant, total N in the grain, and a high nitrogen transfer efficiency, suggesting the possibility of simultaneously selecting for these traits (Hulse et al, 1980).

Generally, the correlation between grain yield and protein is found to be negative but variable. Hybrids almost always produce higher grain yield and frequently have lower protein content than the parents; but, because of the higher grain yield, protein produced per hectare is higher than from the parents or lower yielding varieties.

Inheritance of protein is polygenic. From an experiment at two locations in Kansas both general and specific combining ability (GCA and SCA) were found significant for protein content and heritability was estimated to be 43%. In a number of experiments, heritabilities have ranged from 41 to 85% depending on varieties, populations used, and the method of calculation (Liang et al, 1969).

Although variable, additive gene action for protein inheritance has been found to be less important than the nonadditive component.

Heterosis, calculated as the mean of the F_1s compared with the average of the means of the parents, was found to be significant and negative. Genotypic correlations between percent protein and yield were found to be significant and negative. The same was found for the correlation between protein and lysine as a percentage of protein. In general, genotypic effects on protein content were greater than environmental effects (Hulse et al, 1980).

Amino Acids

"If one looks at the essential amino acid composition of sorghum grain, in comparison with monogastric nutritional requirements, it is obvious that lysine is deficient and that there is great excess of leucine. The methionine content of sorghum is low, but considering the cystine content of 1.5%, the overall sulfur amino acid content approaches the weanling rat requirement. The tryptophan content of sorghum seems to be adequate in contrast to the low tryptophan content in normal maize" (Axtell et al, 1974).

In an experiment conducted in India, Nanda and Rao (1975) found significant differences among hybrids for the traits that they studied; protein content, yield, and a number of amino acids: threonine, methionine, isoleucine, leucine, phenylalanine, cystine, tyrosine, and valine. The parent versus hybrid comparison was significant for yield attributes, lysine, leucine, phenylalanine, glutamic acid, proline, and cystine. Additive gene action contributed more to all attributes except methionine, isoleucine, leucine, phenylalanine, tyrosine, glutamic acid, proline, and alanine, where SCA was significant or predominated over GCA. For protein, lysine, and threonine, GCA was significant.

Significant negative correlations were observed between: protein and yield, seed size, and grain hardness; lysine with isoleucine, leucine, and cystine; leucine with methionine; carotene with protein, methionine, and cystine; methionine, with carotine, threonine, and yield; seed size with threonine; and yield with cystine.

Significant positive correlations were observed between yield with seed size and grain hardness; grain hardness with seed size and lysine; methionine with lysine; isoleucine with threonine; leucine with protein, threonine, and isoleucine; and beta-carotene with lysine, threonine, isoleucine, and leucine (Hulse et al, 1980).

Nanda and Rao (1975) found that the magnitude of additive variance was smaller than nonadditive variance for most amino acids.

The identification of high lysine content in some floury-opaque maize seeds spurred interest in improving protein quality in other cereals. Initially high lysine was found in two sorghum accessions from Ethiopia, IS 11167 and IS 11758. In these accessions, lysine content as percent of sample was approximately twice that of normal. Over 50% of the endosperm protein in sorghum is present in the kafirin fraction which is poor in lysine. It was found in these accessions that there was a shift from 55% kafirin found in normal sorghums to 39%, accounting for the increase in lysine; i.e., the relative concentration of protein components high in lysine increased (Axtell, 1974; Ejeta and Axtell, 1989). Inheritance studies indicated that high lysine was controlled by a single recessive gene designated *hl* (Axtell, 1974).

Seeds from these accessions were shrunken at maturity. It was found that the rate of starch synthesis and level of total sugars at various stages of grain development differed between normal and high-lysine grains. Between 21 and 31 days after pollination, starch synthesis was delayed, and there was an increase of sugars in the high-lysine grains (Ejeta and Axtell, 1987).

The *hl* gene, when homozygous in the endosperm, altered the amino acid pattern. Beside the increase in lysine, there was also an increase in arginine, aspartic acid, glycine, and tryptophan, and a decrease in the concentration of glutamic acid, proline, alanine, and leucine (Singh and Axtell, 1973).

A second approach was to use a mutagenic agent, diethyl sulfate. From 23,000 M_3 heads, 475 were found segregating for opaque. Thirty-three were found with at least a 50% increase in lysine, and P721 had an increase of 60% (Axtell, 1974).

Opaque seeds from P721 were 11 to 14% lower in seed weight than normals. Dry matter accumulation in the seeds of P721 stopped at 31 days, seven days earlier than in normals. Also associated with the floury opaque endosperm were slower rates of drying at harvest, greater mold and insect susceptibility, and more grain cracking following threshing than found in normals (Ejeta and Axtell, 1990). This resulted in problems of acceptance as it did for *opaque-2* maize. To attempt to resolve this problem, hundreds of crosses were made between P721 and an array of other parents to diversify the genetic background. One hundred and fifty-eight lines with high lysine were tested internationally, and both opaque and vitreous types exceeded eight tons of grain per hectare, indicating that opaque seeds could yield well. Several high-lysine lines with vitreous endosperm were identified. Vitreous high-lysine types were also identified by treating P721 with diethyl sulfate. Generally, the vitreous seeds had higher kernel weight with lower protein and lysine contents than opaque seeds (Axtell and Ejeta, 1990). While vitreous high-lysine types were found, it was disturbing that the modification to vitreousness was unstable and would vary from generation to generation even when sowings were made from well-developed vitreous seeds (Ejeta and Axtell, 1990). Additional effort is required to realize commercial application of high-lysine sorghum.

Carbohydrates

The information available on seed carbohydrates in sorghum relates to waxy and sugary endosperm types. Endosperm texture, an important consideration for the preparation of foods, ranges from completely corneous to very floury types, reflecting the degree of protein matrix holding carbohydrate particles. Some corneous types pop well and are used in the preparation of snacks.

The starch in normal sorghum is approximately 25% amylose and 75% amylopectin. The starch in waxy kernels is almost all amylopectin. Normal endosperm stains blue with iodine, whereas that of waxy starch stains red. Waxy is inherited as a single recessive gene; the gene must be recessive at all three loci in the endosperm for the trait to be expressed. Xenia is expressed in the individual arising from fertilization with pollen from a normal plant; i.e., pollen from a normal plant fertilizing ovules of a waxy plant will result in normal seeds.

Waxy sorghum has been used for feed but the advantage compared with normal grain is slight. Waxy grain was used during World War II to make a tapioca substitute (Rooney and Miller, 1982). Waxy sorghum has been used to make specialty foods in China but generally does not make good traditional type foods.

The sugary trait is inherited as a simple recessive gene. At maturity the kernel is crystalline and shrunken in appearance. Sugary seeds are about 25% smaller than normal but contain about twice as much or more sugars than normal. Reducing sugars ranged from 2.52 to 2.67% compared with 0.34% in normal (Hulse et al, 1980). Starch content in sugary lines is much reduced, ranging from 22.2% to 34.0% compared with normal sorghum (60.8%). Amylose content of the starch in sugary lines ranged from 22 to 62% higher than in normal. Water-soluble protein in sugary is higher than that in normal.

There are several sugary genes (dented *R*, *W*, and *F*) and defective traits that influence kernel carbohydrate, but they are of no economic interest.

In some countries, sugary grains are harvested in the dough stage and parched to use as a snack.

Tannins

Tannins, a group of high molecular weight polyphenols, occur in the testa. The presence of a testa is determined by a pair of complementary genes, B_1 and B_2. Fragments of testa may be present in some sorghums if recessive b_1 or b_2 is present. In the presence of B_1 and B_2 and the recessive *tptp*, the testa is purple, and in the presence of *Tp*—it is brown (Doggett, 1988). *S* is a spreader gene and in the presence of B_1 and B_2 results in a brown color in the pericarp. If the testa is fragmented, brown spots occur in the pericarp above the fragments.

High tannin, not lysine, is the primary nutrient-limiting component in sorghum grain.

Initially, it was thought that tannins would bind with endosperm proteins, reducing their biological value; i.e., the complexed proteins were not easily digested. More recent observation indicates that the primary antinutritional effect is the inhibition of the metabolism of digested and absorbed nutrients, especially protein (Ejeta et al, 1989). Polyphenols are in high concentration in the grains with a brown pericarp and pigmented testa, but all polyphenols involved may not act as tannins. It was demonstrated that rat weight gain was significantly reduced as tannin content increased (Ejeta et al, 1989). Cummins and Axtell identified a polyphenol group (type II) occurring in seeds that have a colored testa, usually purple, with vanillin-hydrochloride values less than one and catachin equivalents of no more than two. In rat feeding tests, the protein efficiency ratio was as good as that of white grain (0.63 and 0.58). These types may not repel birds or hold down molds anymore than white types (without testa) (Doggett, 1988). However, once it became possible to highly purify tannin, it was not possible to distinguish the tannins between group II and group III sorghums (Ejeta et al, 1989).

In both group II and group III sorghums, the polymerization that occurs to form large molecules of tannin takes place following wounding of the tissue or grain drying at maturity. Proteins differ significantly in their affinity for tannins; the proline-rich proteins generally have a strong affinity for tannin (Ejeta et al, 1989).

High-tannin sorghums have been cultivated in a number of places in the world where birds are a serious problem. Such grains were usually processed to reduce their negative impact on nutrient value. Dehulling improves the biological value substantially. Traditionally the negative impact has been reduced by treating with wood ash and by malting (Mukuru, 1990). It has been found that treatment with a base such as NaOH reduces toxic effects. Beside the antinutritional aspect, color of testa and pericarp add a color to food that does not occur in food from pearly white sorghum.

Oil

Oil is found primarily in the embryo. Oil content has been found to be positively correlated with protein content, so both traits can be selected for simultaneously. Additive gene action was found to be significant for the inheritance of oil content in some experiments and dominance variance in others. The magnitude of additive variance ranged from quite small to large (Hulse et al, 1980).

Other Grain Traits

Grain color can occur in the pericarp, testa, and endosperm. Color of the testa can be seen if the pericarp has no color and little starch. For endosperm color to be visible, it is necessary to have both a colorless pericarp and no testa.

There are a number of genes affecting grain color. The B_1, B_2, and *Tp* genes were mentioned in the discussion of testa and tannin. A number of genes influence pericarp color. The presence of *Y* results in a yellow pericarp. The presence of *R* results in a red pericarp but only in the presence of *Y* (Doggett, 1988). Colorless or white pericarp occurs when the genetic composition is *R—yy* or *rryy* (Rooney and Miller, 1982). The gene *I* augments the intensity of expression of *Y—* and *Y—R—*. Kernels that are *R—Y—I—* appear bright red compared with *R—Y—ii*. The gene *I* intensifies the lemon yellow color of the pericarp. The gene *M* also modifies the expression of *Y* and *YR*. Bw_1 and Bw_2 result in a brown wash in the pericarp if the spreader gene is recessive (*ss*). As indicated in the previous section, when dominant *S* (spreader) is present with B_1—B_2—, the pericarp color is brown. Rs_1—sunred causes the pericarp to turn red when exposed to the sun at the time the grain matures. The presence of *Pb* results in purple blotches and *Pt* a purple tip on the grain.

A thin pericarp occurs in the presence of the *Z*-gene. Thin pericarp is translucent, permitting testa and endosperm color to show. If there is no testa and the endosperm is corneous, the grain has a pearly white appearance. Grain of this type, particularly in a plant with tan plant color, is preferred by many sorghum consumers, particularly in India, for the preparation of food. If the plant color is red or purple, color may appear in food prepared from pearly white grain. The pericarp varies greatly in thickness, particularly the mesocarp, which can range from 12 to 120 µm. The thicker cells usually contain starch granules. The thick pericarp is associated with a chalky appearance of the grain and can mask or modify color expression. In some crosses *Z* and *S* may interact such that *ZZSS* or *ZZss* results in pearly grain, *zzss* in a chalky mesocarp and *zzSS* in a thin chalky pericarp (Doggett, 1988). Traditionally, in India and much of Africa, round grain with a thick pericarp is liked because it pearls easily by traditional methods.

Damage to the grain by insects or diseases results in spots or blotches of color depending on the presence of *P* or *Q* genes. In continuous wet weather, pigment can penetrate from the testa into the endosperm or from the glumes into the pericarp. These colors result in discoloration of food products. Extensive mold attack can result in loss of grain weight, increase in floury endosperm, and finally in loss of usable grain. Sprouting of the grain in the head can also result if the period of grain maturation coincides with warm temperature and heavy rain or excessive moisture.

Endosperm color is either white or yellow; yellow is controlled by the gene *Ye*. A kernel with a red colored pericarp over a yellow endosperm has a bronze appearance (Rooney and Miller, 1982).

Endosperm hardness (texture) varies with variety; for example, the seeds of the guineas grown in West Africa are completely corneous, while the grain of varieties Safra and Mugud, grown in eastern Sudan, are very floury. These are highly heritable traits.

In some parts of Africa, sorghum is used in the brewing of beer, more frequently as adjunct, but also for malt. In southern Africa, the traditional opaque beer is produced commercially. There is a tremendous range in diastatic power among sorghum types, from less than 10 to more than 60 diastatic units. The desired level for opaque beer is around 30 units. The trait is heritable and selection is possible, but there is an important environmental component. Sorghum diastatic units per gram of malt relates to the conversion of starch to sugars. It is used in the calculation of diastatic power (Daiber, 1971).

FORAGE CHARACTERISTICS OF SORGHUM

Sorghum, sudangrass, and the cross between them are commonly used for animal feed: pasture, hay, and silage. The crop is sown thick and usually cut around the boot stage; three or four cuts or more are commonly taken during a growing season. There are a number of genetic traits contributing to forage uses.

There is a cyanogenic glycoside called dhurrin found in sorghum. It varies with variety and is in highest concentration during the seedling stage. Some 45 days after emergence, the danger from dhurrin is past.

When dhurrin is hydrolyzed, it breaks down into HCN (prussic acid) and *p*-hydroxybenzaldehyde. A cow can be killed by as little as 0.5 g of HCN. Environmental factors such as drought or frost, particularly in the seedling stage, that break down tissue result in the formation of HCN, and the crop can be dangerous to feed. The making of hay or silage results in the loss of HCN, and the feed is safe. Small amounts of glucose and maltose fed to animals reduce the amount of hydrolysis and release of HCN. The feeding of concentrates prior to putting animals to pasture also reduces the danger from poisoning.

There have been a number of studies on the inheritance of high dhurrin content. The inheritance has been reported to be recessive, partially dominant, and dominant. Inheritance appears to be multigenic. Selection for low prussic acid has been effective and varieties with low prussic acid content have been identified (Doggett, 1988.

Brown Midrib

A number of brown midrib genes (*bmr*) have been identified in sorghum, and some (*bmr* 6, 12, and 18) reduce the lignin content and modify the lignin molecule improving animal digestibility by 20–30%. Lignin is not digested and limits the breakdown of cell wall polysaccharides. The phenotypic expression of this trait is a reddish brown color in the midribs of leaves. Expression begins in the four- to six-leaf stage of a developing plant. The color may fade as the plant matures, being difficult to see at maturity.

Inheritance of the *bmr* trait is by simple recessive genes. Allelism tests indicate that *bmr* 12 and 18 may be linked but *bmr* 6 is independent. Brown midrib genes have been induced in sorghum and pearl millet using mutagens, and they have been found naturally in maize and pearl millet and sorghum. Chemically induced mutants in sorghum have reduced lignin content in the leaves from 5 to 25% and in the stem from 5 to 51%. Increased digestibility of some *bmr* lines compared with their near isogenic counterpart was as much as 33% (Cherney et al, 1991).

Other Forage Traits

The stem of sorghum can be insipid or sweet, dry or juicy. Traditionally, sweet juicy stems are used for chewing. There have been indications that sweet juicy stems result in a more palatable forage. The sugar content of sorghum stems can be near to that of sugarcane, and the juice has been expressed commercially to make syrup, refined sugar, and traditionally in some parts of the world (India, for example) to make a caramelized product.

Sorghum plants may senesce, dry, and become brown as grain matures, or leaves and stems may stay green long after the grain matures and dries. The stay-green trait contributes to drought tolerance and resistance to the stress-related disease, charcoal rot.

There is a varietal type known as broomcorn. The panicle has a very short central rachis and very long panicle branches. Broomcorn is grown commercially as a source of material to manufacture brooms.

GENETICS OF MILLET GRAIN CHARACTERISTICS

Pearl Millet

GENERAL

"Pearl millet kernels are about one-third the size of sorghum kernels. The average weight of each kernel is about 9 mg compared with 20–30 mg for sorghum. Sorghum kernels are generally spherical in shape; however, pearl millet kernels are generally tear shaped. The most common color is a slate gray, but colors from creamy white through yellow to black are known. The germ of pearl millet is a much larger percentage of the total kernel than is the germ of sorghum (17.4% compared with 9.8% in sorghum). This difference explains in part the higher protein and oil contents of pearl millet as compared to sorghum" (Sullivan et al, 1990).

The protein content of pearl millet ranges from 8 to 19%. Pearl millet is low in lysine, tryptophan, threonine, and the sulfur-containing amino acids. In an evaluation of several cereals, methionine content was found to be highest in proso, followed by sorghum, pearl millet, and then maize. The level of lysine content of pearl millet grain on a dry matter basis was 0.357%, 21% greater than corn and 36% greater than low-tannin sorghum (Sullivan et al, 1990). With increasing protein content, lysine as a percent of protein decreases, but as yields go up, the total lysine per hectare will increase. Generally the amino acid profile of pearl millet compares favorably with that of wheat, barley, and rice (Hulse et al, 1980).

Starch represents about 56 to 65% of the kernel and is about 20 to 22% amylose; free sugars range from 2.6 to 2.8% of the grain, with sucrose representing about 66% of the total sugars (Sullivan et al, 1990).

Ether-extractable lipids range from 3.0 to 7.4%. They are mostly in the germ and similar in composition to sorghum. There is a "mousy" odor associated with whole milled grain that was thought to be due to rancidity of the oil, but it has been found to be associated with a flavinoid, apigenin, found primarily in grains with a slate gray color. Oxidation of lipids is still considered to be a contributing factor (Hulse et al, 1980).

The carotene content of yellow endosperm pearl millet is similar to that of sorghum and lower than for maize.

Pearl millet is generally not troubled with antinutritional factors, although phytic acid and two trypsin inhibitors have been found (Sullivan et al, 1990). A thionamide-like substance has been identified that interferes with the formation of a thyroid hormone contributing to undesirable gastrogenic effects.

PROTEIN AND AMINO ACIDS

The relationship of yield to protein and lysine content was carefully evaluated at ICRISAT, and results were presented in their annual reports from 1975–1976 to 1983. A negative but low correlation (–0.15 to –0.50) was found between yield and protein content (1977–1978). The variability for protein (5.1 to 18.2%) and for lysine (1.6 to 4.7 g/100 g of protein) contents were found to be high (1975–1976) and, coupled with the weak correlation coefficient, suggested the possibility of breeding for high-yielding, high-protein types (1983). Fractionation of the protein of a number of varieties indicated that albumins and globulins ranged from 22 to 28% of total N, prolamin and prolamin-like fractions from 22 to 35%, and glutelin and glutelin-like fractions from 28 to 32%, indicating that the prolamin fraction in pearl millet is smaller than in sorghum. A hybrid, ICH 105, consistently had a low prolamin content in all locations, which resulted in a high-lysine content (1977–1978). After six generations of pedigree selection, 440 progenies ranged from 14.0 to 23.3% grain protein (1983). After four cycles of selection, 22 high-yielding, full sib progenies with above average protein content (mean, 12.9%) and an estimated lysine content of 2.9% (of protein) were selected to be used for the fifth cycle (1979–1980). From crosses between lines selected for high protein, 18 F_1s showed 14.1 to 15.8% grain protein, and five yielded as well as the high-yielding variety BJ104, which had a protein level of 11.7% (1983). It appears possible with pearl millet to select for yield and protein content and keep a reasonable level of lysine.

Considerable environmental variation for protein content exists. There has been no consistent expression of heterosis. As in other cereals, it appears that the inheritance of protein involves many genes, most of them recessive. In different experiments, additive variance was found to be small, while dominance and epistatic effects appeared to be greater. The predominance of nonadditive effects indicates that diversity of alleles rather than heterozygosity contributed to adaptive changes (Hulse et al, 1980).

Nonadditive variance was also found to be of greater importance in the inheritance of tryptophan, methionine, and total sulfur. Although of less importance, additive effects were also found to be significant.

Godawat and Kaul (1981) evaluated protein, tryptophan, lysine, and threonine content and 1,000-grain weight. The highest genotypic coefficient of variation was observed for protein content. Estimates of broad sense heritabilities were highest for 1,000-grain weight and lowest for lysine content. Protein content was positively correlated with tryptophan content and 1,000-grain weight.

Burton et al (1980) studied the effect of male and female gametes on 1,000-grain weight, nitrogen content, proline content, the nitrogen-proline ratio, and dye-binding capacity, and found that the genetic effects for female gametes were significant for all traits, but for male gametes, significant effects were found for 1,000-grain weight, proline content, and nitrogen-proline ratio.

Gupta et al (1976) evaluated protein content, mineral content, and grain yield of 46 lines from India, Africa, and America grown in India. Tiller number and grain size had the greatest effect on yield. Earing span (time of flowering from tip to base of panicle) had a direct effect on protein content. Plant mineral content has a direct effect on plant height, length of the vegetative period, grain size, and yield.

Gartan et al (1987), from an incomplete diallel analysis, found a predominance of nonadditive variance for the inheritance of protein content, although the heritability estimate was low. Tyagi and Paroda (1982), in a study involving six environments, found a preponderance of nonadditive variance for protein content.

Kumar et al (1983) found no significant correlation between grain yield and protein content. Likewise dye-binding capacity (estimate of basic amino acids in protein) and protein content were not significantly correlated.

CARBOHYDRATES

Gupta and Indoo (1983, *personal communication*) studied the changes in activity of peroxidase and amylase and contents of soluble proteins and soluble sugars at 14 stages of plant development of six pearl millet inbreds and their crosses. They observed that plasticity of plant response in its environment was related to biochemical versatility as plants were able to quickly utilize soluble sugars and proteins in early stages of germination. Both amylase and peroxidase activities were highest during the seedling phase and lowest in the reproductive phase. At different developmental stages, the relative level of recessive and dominant gene action was found to vary based on changes in biochemical constituents.

Champingy et al (1982) studied the growth and accumulation of starch by the parents and F_1 hybrids obtained by crossing one ecotype of *Pennisetum mollissimum* and a cultivar of *Pennisetum glaucum.* Leaves of 25-day-old seedlings of *P. mollissimum* were twice as long as those of *P. glaucum.* Studies of reciprocal F_1 hybrids revealed that each hybrid exhibited heterosis for leaf length in relation to its male parent. Many starch grains were observed in the bundle sheath chloroplasts of *P. mollissimum* and of the hybrid *P. glaucum* × *P. mollissimum.* Quantitative analysis of leaf starch during seedling growth confirmed the observation. Fast growth was associated with starch accumulation, and each hybrid behaved like its male parent.

Khangura et al (1980) analyzed the combining ability of beta-carotene, total carotenoids and other grain characteristics in pearl millet. They observed that specific combining ability was more important than general combining ability for all traits. In a similar study, Bhardwaj et al (1987) showed the absence of non-allelic interaction in the inheritance of grain hardness and beta-carotene. Additive and nonadditive gene effects were important with nonadditive predominating. Grain hardness was controlled by dominant genes and beta-carotene by recessive genes. High heritability was observed for total carotenoids and beta-carotene.

Pande et al (1985) investigated grain sink activity in pearl millet inbreds and the hybrid from crossing them. They observed heterosis for grain starch and protein content in the grain of hybrids.

LIPIDS, FATTY ACIDS, AND FAT CONTENT

Singh and Gupta (1987) observed significant genetic variability for crude protein, soluble protein, total lipids, and fatty acids in a 12 × 12 diallel cross. Additive gene effects were predominant for all traits, and maternal effects were observed for fatty acids only. Estimates of specific combining ability were low, indicating lesser scope for exploitation of heterosis. In a study on genetics of yield and some quality traits in pearl millet, Sachdeva (1981) observed moderate narrow sense heritability for fat content.

FORAGE CHARACTERISTICS OF PEARL MILLET

Pearl millet is widely used as forage. Much work has been done in the United States at Tifton, Georgia, to develop pearl millet varieties and hybrids for feed. Much has also been learned about the management of pearl millet as a feed crop.

Brown Midrib

Brown midrib (*bmr*) genes have been found naturally and as a consequence of exposure to a mutagenic agent (diethyl sulfate). These genes appear to be inherited as simple recessive traits. As with sorghum and maize, the concentration of lignin was reduced (40 g/kg in *bmr* compared with 50 g/kg in the normal counterpart). The reduction of alkalilabile phenolics is not as much as it is in sorghum. At anthesis, digestibility of *bmr* was found to be 726 g/kg versus 659 g/kg for normal. Experimental results support the theory that a 10 g/kg reduction in lignin results in a 40 g/kg increase in digestibility (Cherney et al, 1991).

Other Forage Traits

Forage pearl millet is free of HCN.

The genes *d* (dwarf) and *tr* (trichomeless) have been useful for the improvement of forage quality. The dwarfing gene d_2 results in as much as a 50% reduction in plant height, but leaf number remains the same; the greatest feed value is in the leaves. Dwarf plants, although with lower dry matter yield, have 15% more protein and 17% less lignin, and animal gains are higher than from taller plants.

The trichomeless trait is inherited as a single recessive gene. It improves palatability and contributes to drought tolerance. These positive aspects are balanced by slower digestion contributing to reduced feed intake.

The orange node trait (*on*) resembles the *bmr* trait in improving forage digestibility. Crosses between *on* and *bmr* indicate that these traits are controlled by genes at the same locus.

Heterosis has been found in hybrid pearl millet forage. It has been found that hybrids produced with a pollinator that does not restore male fertility in the hybrid improves forage quality, provides longer grazing, and yields better under stress (Andrews and Kumar, 1992).

CROSSES WITH NAPIER GRASS

The cross between pearl millet and napier grass provides a useful forage plant. With adequate moisture and fertility, dry matter yields of 80 t/ha have been realized, falling to 10 t/ha or less as environmental stress increases. In southern Africa this hybrid is referred to as banagrass. Breeding to improve banagrass was undertaken as part of the SADC/ICRISAT Sorghum and Millets Improvement Program. Yield increases of 50% of the control and protein content of 14% were achieved. Banagrass has withstood severe moisture stress and survived winter temperatures of 0–5°C. Its rapid regrowth following cutting has been attractive to farmers in Zimbabwe.

OTHER MILLETS

Kostantinov in Russia crossed high-protein lines of foxtail millet with low protein lines of common millet. Protein content in the F_1 hybrids was similar to midparent values. In the F_2, the range of protein content was large—14 to 20%. It was noted that red seeds had higher protein content than creamy or yellow ones.

He treated common millet with a mutagenic agents and found three mutants with improved yield, equivalent milling quality, but lower protein quality. Other mutants had 16% protein compared with 14.9% for the untreated control and 12.9% for the standard line (Hulse et al, 1980).

AGRONOMY: NUTRITIONAL CONSIDERATIONS

The section on agronomy is divided; the first part relates to the interaction of agronomic practices on protein and amino acid composition of sorghum and then the millets. A later section outlines interactions of plant nutrients and moisture on plant performance. This division of the agronomic section keeps both heritable and crop management considerations relative to nutritional factors together and places management of crop performance with other crop considerations.

Sorghum

PROTEIN AND AMINO ACIDS

The percent protein in sorghum grain is influenced by variety and by the environment. Significant interactions have been found for variety, fertilization (in amount, in kind of fertilizer, and in methods of application), location, and season. A number of experiments indicate a greater effect of variety than environment on protein content.

Response to application of N fertilizer has been variable: significant in some cases, significant in one or more seasons in a multiseason experiment, or not significant. Applications of phosphorous and potassium fertilizers usually do not influence the protein content of the grain; however, application of fertilizer that resulted in increased grain yield resulted in a greater protein yield per hectare.

There is an effect of location on amino acids. One study in India involving three locations and eight sorghum varieties evaluated the effect on protein and several amino acids: lysine, isoleucine, leucine, methionine, and tryptophan. Protein content varied from 8.1 to 10.5% across varieties and from 6.4 to 11.2% (mean of the eight varieties) across locations. In the location with low protein content, the concentration of the five amino acids as a percentage of protein was higher. In the experiment as a whole, there were negative correlations between protein and lysine, methionine, and tryptophan; lysine and leucine; protein and leucine; and protein and isoleucine (Hulse et al, 1980).

Several experiments have indicated that the change in percent protein is generally due to an increase in the prolamin fraction, with little effect on the albumin and globulin fractions. This indicates that an increase in percent protein is not associated with an improvement in protein quality. In an experiment comparing soil and foliar applications, it was found that foliar application increased protein yield.

The prolamin content increased with nitrogen application (up to 180 kg/ha of N). The glutelin fraction did not increase much beyond 60 kg/ha application, and foliar application was the same as for soil. At 180 kg/ha of N application, protein content increased from 8.9 to 11.6%, associated with an increase in glutamic acid, proline, alanine, aspartic acid, and cystine but a decrease in lysine, histidine, arginine, and phenylalanine (mg/g of N). The leucine-isoleucine ratio increased from 2.5 to 3 as nitrogen application increased from 0 to 180 kg/ha (Warsi and Wright, 1973).

In an experiment in Australia involving six varieties of sorghum and four levels of nitrogen fertilization (0, 68, 136, and 173 kg/ha), it was found that the three basic amino acids, lysine, histidine, and arginine, were negatively correlated with protein content, and other amino acids showed a positive relationship. Only leucine and threonine were significantly affected by nitrogen fertilization and variety (McKenzie and Wallace, 1954).

Results of an experiment conducted in Kansas indicated that the content of protein and amino acids increases in the grain, but the increase in amino acids is not proportional to the increase in protein with increasing N fertilization. There were significant increases (mg/g of N) in glutamic acid, proline, alanine, isoleucine, leucine, and phenylalanine, and a decrease in lysine, histidine, arginine, threonine, and glycine. Changes for aspartic acid, serine, half-cystine, valine, methionine, and tyrosine were not significant. Only glutamic acid, alanine, and leucine were significantly changed due to location (mg/100 g of grain). Expressed as mg/100 g of total N, lysine, histidine, arginine, glutamic acid, glycine, alanine, half-cystine, methionine, and leucine were significantly affected (Waggle et al, 1967).

Different levels of application of P_2O_5 and K_2O fertilizer have not been found to influence levels of protein or lysine and leucine. While K_2O had no effect, P_2O_5 resulted in a significant increase in the concentrations of Ca, Mg, P, Fe, and Mn in the grain (Deosthale et al, 1972).

It has been found that as protein content increased with increased fertilization that the starch content decreased.

In central Sudan, in a three-year study, the crude protein content increased when sowing was delayed from the end of June to the end of August, but yield declined with sowings after the fourth week of July. The decrease in yield was associated with an increase in N and P content, but the increase was not proportional to the loss in yield (Rai, 1964).

Plant population was found to have no significant effect on protein, lysine, or leucine contents.

OTHER TRAITS

Location was found to have a significant effect on the contents of Ca, P, Fe, Mg, Mn, Zn, and Mo in sorghum. The effect on Cu was not significant. Varietal differences for these elements were found to be not significant. Fe was the only element found to be significantly associated with protein (Deosthale et al, 1972).

An experiment in India indicated a high level of variation in carotene content with location. Beta-carotene content continues to decline while grain is in storage.

The above information has been summarized from (Hulse et al, 1980).

Pearl Millet

A comparison of soil and foliar (urea) application of N was studied. Urea application had a significant impact on increasing grain weight. Protein content was

also increased significantly with greatest increase coming at 45 kg N/ha. Effects of N fertilization on fat, fiber, ash, and P_2O_5 were not significant. The Ca content increased significantly at low levels of fertilization (11 kg N/ha foliar and 22 kg N/ha soil application). As fertilization increased, carbohydrate content decreased (Khanna, 1966).

In another experiment with application of N fertilizer from 0 to 200 kg N/ha, yield increased from 1,100 to 1,500 kg/ha and protein 6.7 to 8.1%. Again, with N ranging from 0 to 50 + 50 kg/ha (split application), yield ranged from 781 to 2,178 kg/ha and protein from 7.3 to 13.6% (Blondel, 1970).

An experiment in Senegal with nitrogen fertilization ranging from 0 to 150 kg/ha resulted in a marked increase in protein content, the increase being linear with N application. Increased N fertilization resulted in increased glutamic acid and leucine in the protein and decreased lysine, glycine, histidine, arginine, and to a small degree threonine. As the range of N fertilizer increased from 0 to 50 kg/ha, the average decrease in essential amino acids was less than 2% of the protein. There was no significant change in moisture, ash, lipid, cellulose, Fe, Ca, and P with increasing N fertilization (Ganry and Bideau, 1974).

An experiment was conducted in India using $(NH_4)_2SO_4$ as a source of fertilizer. Application was made at 0, 44, 88, and 176 kg N/ha. Both protein and sulfur content increased significantly at 44 kg/ha of N, and there was a significant increase in the concentration of tryptophan. Above this rate of fertilization, there was an increase of lysine in the grain but a reduction as percentage of protein. The increase in protein content resulted from a 40% increase in the prolamin fraction, with decrease in the albumin and globulin fractions. This resulted in a redistribution of sulfur in the protein fractions; sulfur in the prolamin fraction increased from 20 to 30%, stayed the same in the albumin fraction (20%), and decreased in the globulin fraction (from 28 to 19%).

It was found in pearl millet that the amount of tryptophan in the prolamin fraction is higher than in sorghum and maize (Sawhney and Naik, 1969).

A comparison of seed rate of 2.5 versus 5.0 kg/ha at sowing had no effect on protein content (Tomer, 1970).

Iron and manganese in the seed increased with increasing N fertilization. The concentration of Ca and Mn were found to be inversely related (Shukla and Bhatia, 1971). Thiamin content in the grain was also found to increase with increasing N fertilization.

Finger Millet

As with sorghum and pearl millet, the concentration of protein increased with increasing N fertilization, but there was no consistent pattern with P_2O_5 or K_2O_5 (Venkataramana and Krishna Rao, 1961). The level of Ca fell with increasing application of nitrogen fertilizer (Krishnamurthy, 1968).

As the content of protein increased, the levels of lysine and the sulfur amino acids methionine and cystine as a percentage of total N decreased (Stabursvik and Heide, 1974).

Finger millet has a relatively high content of sulfur-containing amino acids. With fertilization, methionine and cystine increased to about 8% of protein then leveled off. Fertilization, in a ratio of 1:10 sulfur-nitrogen has been found to be appropriate for finger millet (Stabursvik and Heide, 1974).

AGRONOMY: MANAGEMENT ASPECTS

Crop Fertility

From a practical point of view, agronomy involves the management of adapted plants in sole or mixed crop situations; nutrient and moisture availability; cultural practices with respect to sowing and weed management; and to some degree, the expression of pests. Traditionally, sorghum and the millets frequently are not fertilized or are fertilized with animal manure. With some traditional varieties, selected under these conditions for long periods of time, response to fertilizer is reduced compared with varieties and hybrids selected to significantly benefit from good levels of fertility. Several experiments performed in India in the 1960s and later at ICRISAT demonstrated that there is little or no interaction between sorghum variety and response to fertilization. Differences between lines to be selected are greater at high levels of fertility than at low levels. Greater differences facilitate selection. In the absence of interaction between yield and fertility, entries selected at high fertility will also perform better at lower levels of fertility justifying the use of fertilizer in breeding nurseries.

Nutrients may not be limiting. This needs to be determined for each environment. If commercial fertilizers are used by traditional farmers, 30 kg/ha of N, with half to the same amount of P_2O_5, and some K_2O is common, and there is plant response. Unless it is very dry, application of 80 kg of N/ha is economic, and application above 120 kg of N/ha is not as common in countries where most of the agriculture remains traditional.

In situations where rainfall is in the 250 to 500 mm range, distribution of rainfall can be as important as amount. With reasonable distribution and no fertility, yields in the 400 to 800 kg/ha range can be expected, but, with fertility yields can be 1.0 to 2.0 t/ha. With good moisture and fertility, yields of varieties can be 3,000 to 4,000 kg/ha and 5,000 to 6,000 kg/ha for hybrids. Highest yields can reach 8,000 to 12,000 kg/ha depending on length of growing season and good crop management. It is important, but commonly not realized, that hybrids almost always have higher yields than varieties, and while the yields of both drop with poor growing conditions, the magnitude of hybrid yield over varietal yield is the greatest in stressed environments.

R. L. Vanderlip (1979) and his colleagues have studied nutrient uptake by sorghum. They find that curves for nutrient uptake are above those for dry matter accumulation. They point out that at 60 days after emergence, about one-half of the plant weight has been produced, but "nearly 60% of the phosphorous, 70% of the nitrogen, and 80% of the potassium have already been taken up."

Of the three major nutrients, potassium is taken up most rapidly, followed by nitrogen, then phosphorus. Translocation of nutrients to the grain is largely nitrogen and phosphorus with smaller amounts of potassium. A crop with grain yield of 8,500 kg/ha uses approximately 210 kg of nitrogen, 40 kg of phosphorus, and 245 kg of potassium per hectare (Vanderlip, 1979).

Plant growth is slow during the first 20 to 25 days as leaf area (photosynthetic capacity) increases. Leaf growth continues during the next 50 to 80 days, when the upper 8 to 10 leaves develop, providing the important leaf area to produce nutrients for grain production. Following floral initiation, there is rapid stem elongation, followed by flowering and grain formation. Later-maturing varieties and hybrids tend to have more weight at each growth stage. A two-year average of three hybrids indicated a dry matter accumulation of 193 kg/ha per day. Later-maturing hybrids yield more than earlier types—for normally adapted cultivars, yield tends to increase linearly with length of growing period.

Micronutrients are important to plant growth and must be available if high yields are to be realized. Iron concentration was initially high in stems and gradually decreased as the plants developed. Grain and panicle parts remained relatively constant at 75 ppm.

Concentrations of zinc were highest in early stages of growth, particularly in the stems. All plant parts had roughly the same concentration after vegetative growth ceased. About 50% of total zinc uptake was in the grain at physiological maturity (Jacques et al, 1985).

The highest concentration of copper during plant growth was in the stem. Concentration gradually decreased with plant development including grain formation. There was a greater uptake of copper during the vegetative stage than during panicle development and seed formation.

Manganese concentrations differ substantially among plant parts, with higher concentrations in leaf blade and leaf sheaths compared with the stem and panicle. Concentration is higher in younger plants than when they mature. Manganese concentration changes little once maximum dry weight is reached. Leaf sheaths have the highest concentration. At physiological maturity, 50 to 60% of the manganese is in leaf blades and sheath, 5% in culms, and most of the rest in the grain.

Concentrations of magnesium are high in leaf sheaths and remain so throughout the growing season. Concentration in the stems decreases as the season progresses, while it remains fairly constant in leaves. Manganese concentration in the heads is relatively low and decreases as grains reach physiological maturity. Manganese was translocated from the stems into the panicles.

Calcium was found to be lower in the panicles than other plant parts. The concentration of calcium increases in leaves following their attaining maximum weight and during grain formation. Calcium remains in higher concentration in leaf blades than in other plant parts. By contrast, calcium concentration in stems and leaves increases during grain development but remains the same in the sheaths (Jacques et al, 1975).

As with major nutrients, uptake of minor elements preceded dry matter production. Generally, nutrient content changed among plant parts with development, was highest following emergence, and then decreased during the rapid growth stage when nutrient uptake could not keep up with growth and elongation. It is apparent that nutrients should be plentiful during early plant growth. This can be provided by soil application or by spray.

Moisture

Sorghum and millets are crops of semiarid areas, and moisture availability for plant growth is critically important. A characteristic of the semiarid tropics is high variability in amount of rainfall per season and distribution within the season. With an average rainfall of 700 mm, seasonal variation can range from 300 to 1,200 mm. During the period 1980 to 1992 in southwestern Zimbabwe, where long-term average rainfall is around 600 mm per year, rainfall was below expectation every year but two. Even with low rainfall (300 to 350 mm) but with good distribution, plot yields exceeding 3 t/ha of grain have been realized. If there are prolonged breaks in rainfall, particularly at the time of floral initiation or flowering, yield of grain would drop to a ton per hectare or less.

Management of moisture becomes important, particularly when it is generally in short supply but can be excessive in a season with few but heavy rains. Various practices have been developed to manage such rainfall while minimizing soil erosion, such as leaving crop residue, alternating vegetative strips with cultivated strips, drainage systems to carry off water with minimum erosion, furrowing fields so that each furrow carries water onto or off the soil surface. The furrows may be tied; i.e., small barriers are built periodically in the furrow to hold water where it falls. If sufficient power is available, fields may be deep-chiseled periodically to break hard pan and improve water penetration. The important thing is that plans are made to retain adequate water on the land and to drain excess water off the land with minimal soil loss.

Fertility is important to effective moisture utilization. An experiment conducted at Matopos, Zimbabwe, with stubble and 50 kg/ha nitrogen resulted in a yield increase of 8.8 kg/ha per millimeter of rainfall for a total yield of 3,878 kg/ha. Without the stubble and nitrogen treatment, yield increase dropped to 1.6 kg/ha of grain per millimeter of rainfall with a yield of 705 kg/ha. It is difficult to indicate how much fertilizer to use, but approximately 30 to 50 kg of N/ha for rainfall of 250 to 400 mm; 60 to 80 kg of N/ha for rainfall of 400 to 650 mm; and 120 kg N/ha for rainfall of 650 mm and above. Large-scale commercial farmers, especially with irrigation, may use in excess of 150 kg/ha of N. Generally phosphorus is 50 to 100% that of nitrogen, and the need for potassium should be determined.

Traditional farmers, particularly in West Africa, frequently use photoperiod-sensitive varieties. At times, first and second sowings fail, and resowing is necessary. With photoperiod-sensitive types, flowering and grain maturity occur during the same calendar days regardless of planting date, so that even with delayed sowing, plants mature when chances are good that there is moisture to finish the crop.

There are frequently advantages in sowing into dry soil early in the season, as yields are higher with a longer growing period. Deep sowing is advantageous because more moisture is accumulated in the soil before germination. Many sorghum varieties emerge from 5 cm and some from 10 cm. The greater the depth, the more moisture accumulates in the soil before germination and the longer seedlings can survive if rain following emergence is delayed.

Control of weeds, particularly during the seedling stage, is very important; it can be even more important than fertilization. An experiment conducted at Matopos in Zimbabwe is revealing. With no treatment, yield came to 814 kg/ha; with 50 kg of N/ha the yield was 920 kg/ha; with two weedings the yield came to 2,630 kg/ha; and with two weedings and 50 kg of N/ha the yield came to 3,134 kg/ha. Nitrogen fertilization was most effective with weeding.

Plant stand should be lower when moisture is limiting; with nontillering traditional sorghum varieties, stands may be as low as 60,000 plants/ha. With 700 mm of expected rainfall and good management, a plant stand of 180,000 plants/ha is good; with poorer management or fertility a stand of 120,000 would be better. Sorghum and millets have a great capacity to compensate for stand.

Cropping Systems

Different cropping systems, well adapted to different regions where sorghum and millets are grown, have been developed and improved upon by farmers and scientists involved in the production of these crops. The differences in cropping systems are dictated by the technology available to the farmers and the agroclimatic conditions that prevail in a particular region.

INTERCROPPING

The main consideration for mixing crops together is to reduce the risk of total crop failure. Food crops are usually mixed with cash crops to help ensure both sustenance and disposable income. Cereals and legumes are often intercropped more for dietary reasons than for any beneficial effect the nitrogen-fixing powers of the legumes convey to the associated cereal crop or to a subsequent one (Swindale, 1979).

Small-scale farmers are often burdened with the twin problem of low crop productivity and limited land resources. Intercropping provides these farmers with a possible means of increasing crop productivity. Intercropping aims to increase total productivity per unit land area and to equitably and judiciously utilize land resources and farming inputs including labor. One obvious limitation is the reduced population of both crops and the effect on their productivity.

Intercropping is a risk-reducing method of agriculture that is particularly common in traditional agriculture where amount and distribution of rainfall are uncertain. The variety of crops is great, frequently involving a cereal and a legume. Many other combinations of cereals with cereals, with oil crops, or with vegetables are undertaken. The most effective intercrops and their management require evaluation. The two crops should not make peak demand on the environment at the same time. One plant that heavily shades another seriously affects the yield of the shorter crop. Sowing the crops at different times, with different row combinations (two-to-one or three-to-one ratio, etc.) and fertilization are important management considerations. Insect and disease problems may be different in an intercrop than a sole crop, influencing pest management.

Results from intercropping experiments have had variable results. An intercropped pigeon pea in sorghum had higher yield than a sole crop. However, the yield of mung beans in sorghum declined (1.03 to 0.42 t/ha), but the monetary value of the intercrop was greater. The conclusion was that 50% sorghum and 50% mung beans was most profitable (Chaudhry et al, 1987).

When sorghum was intercropped with pearl millet, land equivalent ratios showed no advantage from intercropping. Grain yields were consistently highest from pure stand sorghum. When soil moisture was adequate, yield tended to increase with the later-maturing sorghum varieties in the intercropped system; however, with inadequate moisture, millet was more competitive for water than sorghum. The adverse effects on sorghum outweighed the favorable ones on pearl millet. Sorghum intercropped with finger millet reduced the light available to finger millet, and dry matter produced by the finger millet was reduced (Stutzel and Vanderlip, 1988).

In an intercrop of sorghum and soybeans, the sorghum performance was good, but the soybean performance was much reduced.

In comparative performances of sorghum–pigeon peas, cotton–black gram, cotton-soybeans, pearl millet–pigeon peas, and pigeon peas–pearl millet intercropping systems under dryland conditions in India, it was found that highest net returns were realized with sorghum–pigeon peas followed by the pigeon peas–pearl millet system. The pearl millet–pigeon peas systems however showed the highest water use efficiency on a yield basis, whereas on a net returns basis the highest water use efficiency was for the sorghum–pigeon peas system (Dhoble et al, 1990).

An experiment was carried out in India involving pearl millet with soybeans or cowpeas. Sowing involved pure stands, two rows of legume to one of pearl millet and a mixture of legume and pearl millet sown in the same row. Green fodder and dry matter yields were generally higher for intercrops and seed mixtures than for pure stands. Dry matter yields ranged from 3.65 t/ha for the pure stand of pearl millet to 5.93 t/ha for the mix of soybean and pearl millet sown in the same row (Narwal et al, 1988).

At the ICRISAT Center, groundnuts were intercropped with pearl millet in the ratio of three to one. There were several interesting observations. Wind speed above the groundnuts decreased, and the radiation use efficiency of the groundnuts increased by 21–35%. The uptake of nitrogen by pearl millet increased in the intercrop. The best arrangement was to sow the groundnuts three weeks after the pearl millet.

It was found that indeterminate-spreading cultivars of cowpeas produced greater seed and fodder yield than erect types and caused the greatest millet yield reduction. For best yield results, it was suggested that cowpeas be selected in the intercropped situation.

Finger millet is included in intercrops. At Coimbatore, India, it was intercropped with sorghum, sunflower, okra, onions, and cluster bean. Total biomass production ranged from 11.73 t/ha in the finger millet–onion intercrop to 15.10 t/ha in the finger millet–sunflower intercrop. Finger millet grain yield ranged from 2.72 t/ha when grown in association with sunflower to 4.57 t/ha in pure stand (Siddeswaran et al, 1989). Finger millet production was reduced because of competition with sorghum and sunflowers; light availability was reduced to cluster beans, onions, and okra because of shading by finger millet.

SORGHUM AND MILLETS IN CROP ROTATION

Crop rotation is a sequence of different crops grown on the same land. Generally, the strategy is to improve soil and at the same time gain an income from it. Cropping systems tend to be relatively location specific.

Crop rotation usually involves two or three crops; most frequently one or more cereals alternate with legumes. Rotations can involve summer-winter crops; sorghum or pearl millet with chickpeas or sorghum and millet with wheat or mustard are examples. Sorghum and millet can rotate with summer legumes, pigeon peas, mung beans, cluster beans, etc., and can be rotated with a green manure crop such as sunnhemp, which is plowed in before maturity. Both foxtail and proso millets and sorghum have been used in rotation with transplanted rice.

Incorporation of crop residue and green manure crops and crop rotation improve soil tilth and can reduce nematode and other soilborne problems.

There are examples of application of fertilizer on one crop carrying over to the next. However, residual nitrogen from previous legume crops on a cereal is limited, and addition of commercial fertilizer is important to increasing yield.

When farmers grow cash crops such as chilies, onions, potato, tobacco, etc., they are sometimes followed by finger, pearl, or foxtail millet. Finger millet is also grown (transplanted finger millet) in relay cropping with amaranths.

In China, foxtail millet is grown after corn, sorghum, soybean, or spring wheat. However, repeated cropping of foxtail millet may cause a yield decrease in the succeeding crop; hence, it may be beneficial to have one crop of foxtail millet at an interval of two or three years.

Finger millet is also included in the cropping system of a number of southern and eastern African countries. Some of these cropping systems include finger millet as a mixed crop in rotation or as a sole crop. A millet rotation system might follow the sequence, cotton, millet, cotton, millet, cowpea, groundnut. Finger millet is also preceded by sorghum, maize, peas, beans, or sweet potatoes. A mixture of these crops is also quite common. Sorghum and millets can fit into many cropping patterns.

PLANT DEVELOPMENT AND STRUCTURE

Sorghum

When seeds are sown into moist soil they take up moisture and germination occurs. Emergence of sorghum and millets is usually about three days from sowing in warm climates and around 10 days in temperate areas where soil temperatures are cold at the time of sowing. As the seed swells, the seed coat breaks, and the coleoptile and radicle (primary root) emerge. The coleoptile emerges from the ground, and the first leaf breaks through the tip. The young plant continues to grow, and the coleoptile remains as a sheath at the base of the plant. Frequently, one or more buds are formed at the base of the coleoptile from which tillers arise. Some tiller profusely, especially sudangrass and forage sorghums.

Secondary roots begin to develop when the plant is three to seven days from emergence. About the time that secondary roots begin to develop, the primary root begins to die, and the plant then continues to develop from secondary or adventitious roots.

Cultivated sorghums are annuals or weakly perennial and essentially nonrhizomatous. The roots will continue to live and support ratoon crops (second and third crops from the same roots).

The stem consists of a sequence of nodes and internodes that ranges from 0.5 to 4 m in length and from 0.5 to 5 cm in diameter at the base.

Leaves arise alternately at nodes along the stem. The leaves can be as much as a meter long and 10 to 15 cm wide, although they can be much smaller. In well-adapted plants, the leaf number ranges from 14 to 17, but in less well-adapted types and some very long duration types the number may reach 30. Generally, the embryo has five to seven embryonic leaves, the remainder being formed by the vegetative bud at the tip of the stem. At maturity, a well-adapted plant generally has seven to eight functional leaves after lower leaves have died and dropped.

The vegetative bud becomes a floral bud, usually 30 to 40 days after emergence, although it can range from 17 to 90 days. At this time, all leaves have been formed, and the plant is knee to waist high. This is a period of high moisture demand. Moisture stress during or just after floral initiation can reduce panicle size and floret number. The plant enters the grand period of growth where stem elongation is primarily by cell enlargement. After floral initiation, a panicle develops, and about six to 10 days before flowering, a boot or swelling forms at the top of the plant. Sorghum usually flowers in 55 to 70 days in warm climates, which can be 10–15 days longer in cooler, temperate climates.

Flowering begins at the tip of the panicle and proceeds toward the base, taking four to five days. Sorghum is primarily a self-pollinated crop with 2 to 20% cross-pollination, the percentage being higher on more open-headed panicles. Flowering is another period of high moisture demand; severe moisture stress at this time will reduce yield.

About 10 days after flowering, the seed becomes conspicuous as a green spherical body. It takes about 30–40 days for the seed to reach maximum dry weight (physiological maturity). There are three stages of seed development: milk dough, early dough, and late dough. The seed is green during the milk stage and takes color at soft dough, when the seed is still soft, and juice can be expressed by squeezing. During the hard dough stage, the seed has colored and is firm. At physiological maturity the seed has about 25 to 30% moisture. During the following 20 to 25 days, the seed dries to around 12% moisture, the upper limit for safe storage (House, 1978).

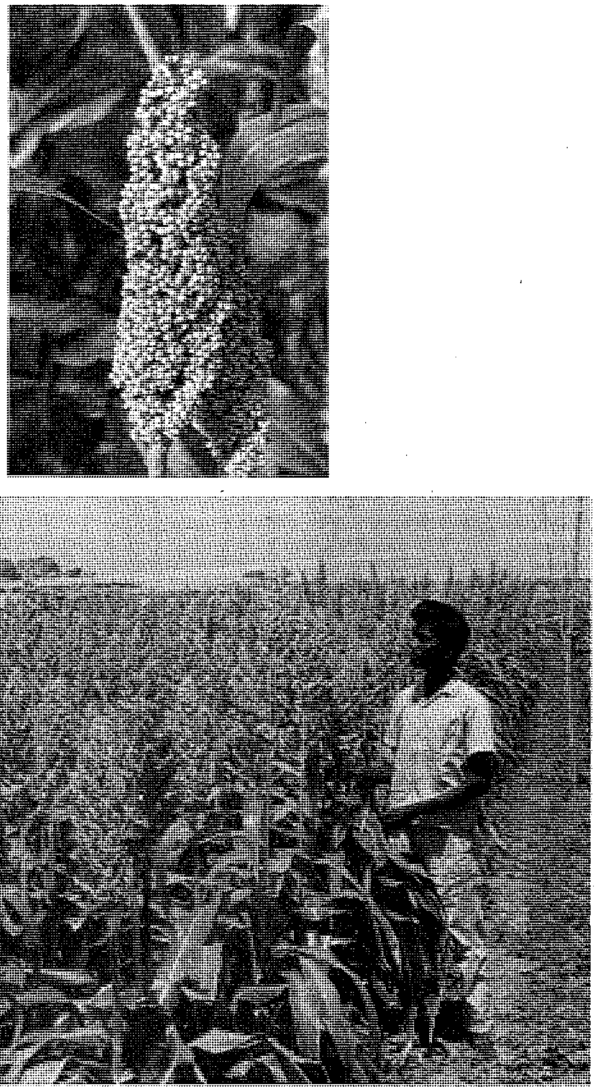

Fig. 1. Sorghum.

TABLE 2
Stages of Sorghum Development[a]

Growth Stage	Days from Emergence	Identifying Characteristic
0	0	Emergence; coleoptile visible at soil surface
1	10	Collar of third leaf visible
2	20	Collar of fifth leaf visible
3	30	Growing point differentiation; approximate eight-leaf stage
4	40	Final leaf visible in whorl
5	50	Boot; head extended in flag leaf sheath
6	60	Half bloom; half of plants at some stage of bloom
7	70	Soft dough
8	85	Hard dough
9	95	Physiological maturity; maximum dry weight

[a] Source: Vanderlip (1979).

The development of the plant is frequently considered to have three stages; emergence to floral initiation, floral initiation to flowering, and flowering to physiological maturity. Vanderlip (1979) refined this to include more stages of development, which has proved useful for agronomic, pathological, and entomological studies. His stages of development are shown in Table 2.

The first 30 to 35 days after emergence, growth is primarily in the leaves. The stem then begins rapid elongation. Leaves and stalks continue growth until about 60 days to maximum leaf weight and 65 days until maximum stalk weight is reached. Panicle weight begins to increase rapidly after 50 days. Following pollination, seed weight rapidly increases, sometimes faster than dry weight accumulation. This results in a decrease in stalk weight as materials move from the stalk to the panicle. The time may vary with maturity—the time from emergence to half bloom is about two-thirds of the time from planting to physiological maturity. For a detailed discussion of stages of sorghum development see Vanderlip (1979).

Pearl Millet

The development and structure of pearl millet is similar to that for sorghum with some exceptions. Pearl millet, an annual grass, generally tillers more profusely than does sorghum, with the exception of sudangrass. Tillering is primarily from basal nodes. Plant heights range generally from 1.2 to about 3.5 m depending on dwarfing genes. Leaves are generally smaller than for sorghum, 90 to 100 cm in length and 5 to 8 cm in width. The stem, on the average, is thinner than for sorghum (1 to 3 cm in diameter). The panicles are long and cylindrical, ranging from 15 cm to a meter in length and 2 to 5 cm in width. At maturity, the stem tends to be more woody than that of sorghum.

Pearl millet is earlier than sorghum, maturing a crop in 80 to 110 days; some varieties are even earlier. It is primarily cross-pollinating, as stigmas emerge one to three days before the anthers (protogynous) and therefore have opportunity to accept foreign pollen. Seeds are one-third to one-half the size of sorghum and tend to be more elongated and tear shaped. Spikelets can be bristled (awned), but in most varieties there are no awns.

Fig. 2. Pearl millet.

Fig. 3. Finger millet.

Finger Millet

Finger millet is a highly tillering annual grass. Average height is a little over 1.0 m but can reach 1.6 m. Tillers come from the base of the plant and axillary buds along the stem. Each tiller or branch produces a panicle. Leaves are generally 30 to 40 cm in length, but can reach 70 cm, and are narrow (1.5 to 3.0 cm). Panicle branches commonly come from the same place giving a fingerlike appearance. The number of branches ranges from four to 19; they can be straight (3 to 10 cm long), or curved like a hand with fingers partially closed. Seeds are formed in florets generally arranged in two rows along the panicle branch. Seeds are generally dark brown, red brown, or purple, although light brown and cream colored seeds are found. Seeds are very small, up to 2-mm in diameter and hard. Seeds of finger millet store well. Some of the brown seeded types have high levels of tannin.

Finger millet is generally grown in higher rainfall areas (600 to 1,200 mm) and is one of the better crops for acid soils. Maturity is reached in from 100 to 130 days.

Foxtail Millet

Foxtail millet is an annual grass that is variable in its morphology. Plants range from single-stemmed to highly tillered. The highly tillering types range from 30 cm to almost a meter, and are grasslike in appearance—each tiller having a panicle pretty well described by its name, foxtail. Panicles are frequently small, 10 to 15

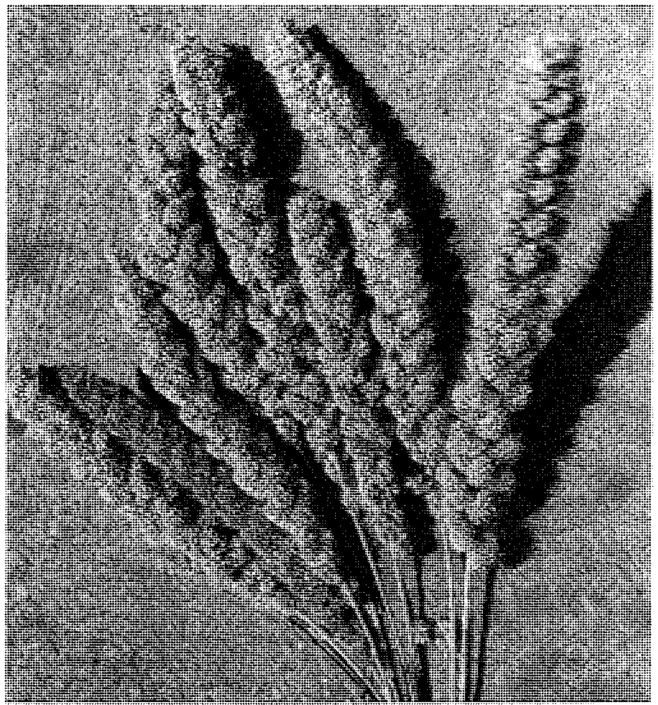

Fig. 4. Foxtail millet.

cm in length and 1.5 to 3 cm in diameter. The central rachis is frequently lax, so the panicle droops. By contrast, some varieties, particularly common in China, are single-stemmed and range from 60–70 cm up to 150 cm tall. Leaves are 30 to 35 cm long and 1.5 to 3.0 cm wide. The panicle has short branches; the central rachis is frequently stiff, but heads on some varieties droop. Panicles can range 12 to 15 cm long and 4 to 6 cm wide at the lower part of the panicle, tapering slightly toward the tip. Seeds are small (2 to 3 mm) and generally light cream colored.

Foxtail millet is adapted to temperate regions although found in the tropics. It has a broad range of maturity, from 70 to 120 days.

Proso

Proso is an annual grass adapted to temperate parts of the world. It is highly variable in its morphology, ranging from as short as 25 cm to 230 cm. Many tillers are formed, each with an open panicle with drooping branches. Panicle branches range from 4–5 cm up to 15 cm in length. Individual seeds weigh from 5 to 9 mg.

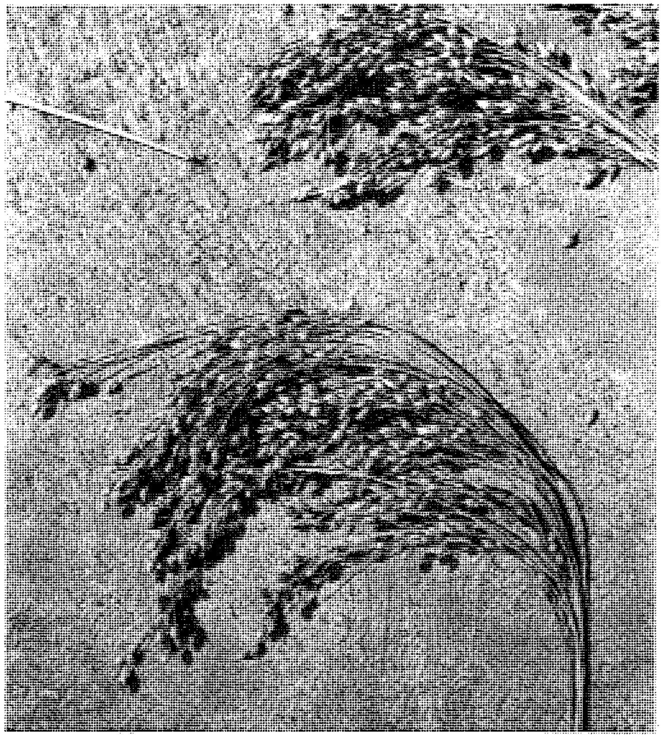

Fig. 5. Proso millet.

Kodo Millet

As a commercial crop, kodo millet is grown only in India. Kodo is an annual millet that varies in height from 30 to 90 cm and has many basal tillers, 10 to 48. The inflorescence is small, 2 to 12 cm. It matures late compared with other small millets. It is highly self-pollinating; florets generally remain closed during the flowering period. The grain occurs in a hard husk, making debranning difficult. The crop is drought hardy and frequently grown on poor soils.

Little Millet

There are two races of little millet, nana and robusta. Plants in race nana vary from 60 to 170 cm in height. The inflorescence is 14 to 15 cm long, erect, open, and highly branched. These branches sometime droop at maturity. Plants in race robusta are 120 to 190 cm tall. The inflorescence is 20 to 45 cm long, open or compact, and highly branched. It is a primarily self-pollinated crop with up to 3.5% cross pollination.

SORGHUM DISEASES

Sorghum suffers from a broad range of pathogens, in part, because of the wide diversity of environments in which it is cultivated. "In the areas where sorghum is traditionally grown, plants may be attacked by as many as five or six foliar pathogens: an array of soilborne organisms including beneficial mycorrhizae, one or more viruses, a mycoplasmalike organism, and at least two systemic fungal diseases. Overlap of symptoms is common in diseases caused by foliar pathogens" (Frederiksen, 1986). Disease identification is further complicated by variation in plant colors and some other morphological characteristics. Visual field identification is frequently difficult and uncertain.

The range of sorghum diseases can be appreciated from the table of contents of the *Compendium of Sorghum Diseases* (Frederiksen, 1986):

- Diseases caused by bacteria: bacterial leaf stripe, bacterial leaf streak, bacterial leaf spot
- Diseases caused by fungi. Foliar diseases: leaf blight, leaf anthracnose, gray leaf spot, zonate leaf spot, sooty stripe, rough leaf spot, oval leaf spot, tar spot, target leaf spot. Smuts and rust: head smut, loose kernel smut, covered kernel smut, long smut, rust. Downy mildews: crazy top, sorghum downy mildew. Root and stalk diseases: anthracnose stalk rot, Fusarium root and stalk rot, charcoal rot, pokkah boeng (twisted top), milo disease, Pythium root rot, Acremonium wilt. Leaf sheath diseases, banded leaf and sheath blight, zonate leaf spot on leaf sheaths, southern sclerotial rot. Panicle and seed diseases: grain mold, head blight, ergot, panicle and grain anthracnose, storage molds
- Diseases caused by viruses and viruslike organisms: maize dwarf mosaic, sugarcane mosaic, brome mosaic, maize stripe, peanut clump, sorghum stunt mosaic, sugarcane Fiji disease, yellow sorghum stunt
- Nematodes: stunt nematodes, root-knot nematodes, cereal root-knot nematodes, *Pratylenchus* spp.
- Parasitic plants: witchweed (*Striga* spp.)

Bacterial Diseases

Three bacterial diseases are important and there are eight more of minor importance. The important ones are bacterial leaf stripe (*Pseudomonas andropogonis*), found most frequently in humid tropical and subtropical regions, and bacterial leaf streak (*Xanthomonas campestris* pv. *holcicola*) and bacterial leaf spot (*P. syringae* pv. *syringae*), which are more common in humid temperate areas.

Generally, yield loss due to bacterial diseases is minor. Bacterial leaf spot occurs on pearl and foxtail millet in addition to sorghum. Symptoms are interveinal lesions on the leaves. The color of the lesion relates to the red, purple, or tan plant color. A water-soaked appearance occurs with leaf streak and leaf spot but not with leaf stripe. Lesions can increase in size and coalesce to form blotches or diseased areas.

Control of these diseases includes use of resistant cultivars, crop rotation, and destruction of crop residue.

Fungal Diseases

Fungal diseases are the most common. "Fungi, perhaps the most abundant plant pathogens, are small organisms that lack chlorophyll and usually grow as filamentous threads called hyphae. They usually reproduce by forming spores, which can be spread by wind, rain, machinery, and other means. Fungi can penetrate plants directly or via natural openings, such as stomata. They survive as spores or resting structures (e.g., sclerotia and teliospores) in soil or plant debris or as hyphae (i.e., mycelium) within living plants or plant debris" (Frederiksen, 1986).

As indicated in the listing of diseases, fungal diseases attack at any stage of development and all plant parts. Several different fungi may be involved. Fungi affecting seedling emergence and early growth are favored by cool damp soils. Generally, humid wet conditions and warm temperatures favor fungal diseases. Some fungal diseases occur after flowering and have minor impact on yield, but if conditions favor earlier disease expression (before flowering), there can be loss of both grain and forage yield.

The first expression of a fungal problem is failure of seeds to germinate. This problem is frequently associated with poor seed quality. After emergence, seedlings may show symptoms varying from leaf necrosis, to stunting, to death (damping off). The root system also suffers, with restricted growth to discoloration and death. *Pythium* spp. are the most important causal organisms.

Fungicides such as captan and thiram have been used with limited effect. Systemic fungicides, such as metalaxyl and fosetyl Al, used with fungicides such as captan and thiram have proven to be effective. The use of good quality seed, and seeds of hybrids rather than varieties (because of increased vigor) help reduce disease damage.

Among the fungi causing foliar disease is leaf blight (*Exserohilum turcicum*). This disease is spread over much of the world where sorghum is grown, particularly where it is humid. Initial expression is small lessons on the leaves that enlarge and can coalesce resulting in dead areas. Characteristic lesions are elliptical, 2.5 to 15 cm long and 1.2 cm wide; older lesions have yellow to gray centers with reddish margins. Control is primarily by use of resistant cultivars; rotation with nonsusceptible cultivars can be advantageous.

Leaf anthracnose (*Colletotrichum graminicola*), gray leaf spot (*Cercospora* sp), and zonate leaf spot (*Gloeocercospora sorghi*) are found around the world where sorghum is grown. If anthracnose becomes severe before flowering, yield reduction follows. Gray leaf spot and zonate leaf spot seldom have much impact on yield. Use of resistant cultivars is an effective means of control, except for zonate leaf spot, where crop rotation and clean cultivation help reduce disease severity.

Sooty stripe (*Ramulispora sorghi*) occurs on sorghum primarily in the central states of the United States and in West Africa. It occurs on sorghum at all stages of development. Initial spots enlarge to form long elliptical or spindle-shaped lesions. As the lesions mature, abundant conidia give a grayish color in the center, which later becomes black. Control by resistance is useful. Destruction of infected leaves will reduce spread; crop rotation will help.

There are several other leaf diseases; the interested reader is referred to the *Compendium of Sorghum Diseases* (Frederiksen, 1986).

SMUTS

There are several head smuts, each different, resulting in different methods of control. The important smuts are head smut (*Sporisorium reilianum*), loose kernel smut (*Sphacelotheca cruenta*), covered kernel smut (*Sporisorium sorghi*), and long smut (*Tolyposporium ehrenbergii*). The panicle is altered by the expression of head smut, with panicle branches being distorted. As the disease matures, panicle structure becomes black with the rupture and release of teliospores. Besides the complete alteration of the panicle, cultivars may be dwarfed, tillering may be more than normal, and the root system may weaken, predisposing infected plants to other diseases.

Infection by loose kernel smut may also reduce plant height and increase tillering. Usually all spikelets are infected. The disease develops on the pistils and stamens and grows to form a black conical body protruding from the glumes. This body ruptures, releasing spores. Control is possible with a fungicidal seed dressing, and highly susceptible cultivars should be avoided.

Covered kernel smut results in infection of the ovules and the eventual production of an oval to cylindrical body (sorus) protruding from the glumes. At maturity, this body ruptures and releases spores. The use of fungicidal seed treatment controls the disease.

Long smut also produces cylindrical, slightly curved but long (2 to 4 cm) sacs that extend from the glumes. Spores develop in these structures that are released at maturity. The best control is the use of resistant varieties. Destruction of newly infected heads and of alternate hosts help provide control.

Head smut is most common in some sorghum-growing areas of Africa, Asia, Australia, Europe, and North America. Loose kernel smut commonly occurs in most sorghum areas of the world except Australia, Oceania, and the Malaysian–Indonesian archipelago. Covered kernel smut is found wherever the crop is grown, and long smut is found in a number of African and Asian countries. Usually, smuts, when they occur, reduce yields.

RUST

Rust (*Puccinia purpurea*) is widespread where sorghum is grown (except in the United States). If the disease occurs before flowering, it can reduce both grain and forage yields. With severe infection, grains shrivel. Rust appearing after grain begins to form generally has little impact on yield but can reduce forage quality.

Rust appears as scattered small (2.0-mm) lesions on both surfaces of the leaves, and is red, purple, or tan depending on plant color. As the disease matures, lesions darken as spores develop, rupture covering tissue, and are dispensed. The use of resistant varieties in areas where the disease is severe offers the best control.

DOWNY MILDEW

Downy mildew (*Peronosclerospora sorghi*) occurs wherever sorghum is grown and can be an important reducer of yield. Infection can be systemic or from lesions on the leaves. Systemic infection can occur in the seedling stage, stunting and killing the plant. Leaves have chlorotic streaks, and in cool climates a white downy growth develops generally on the lower leaf surface, consisting of conidia and conidiophores. Eventually, the chlorotic tissue dies, and the leaves have a shredded appearance. Conidial infection of the leaves results in rough-looking, irregular lesions. The systemic infection is much more common.

A level of control can be achieved by treating seeds with the fungicide, metalaxyl, use of resistant varieties, and crop rotation. In southern Africa, plants from early sowings were less infected than those from later ones.

ROOT AND STALK ROTS

There are a number of root and stalk rots; the more important are Fusarium rots caused by *Fusarium moniliforme*, charcoal rot (*Macrophomina phaseolina*), and milo disease (*Periconia circinata*).

Fusarium moniliforme occurs in tropical and temperate soils, where it causes rots of seed, seedlings, roots, and stalks on a wide range of crops including maize, millet, sudangrass, and sorghum. Crop losses frequently range from 5 to 10% but can destroy a crop. Control of the disease is best achieved by reducing crop stress; i.e., adequate moisture during the growing season, weed and insect control, good fertility, reasonable population, and use of cultivars with good stalk strength.

Plants are conditioned to charcoal rot by stress, frequently from drought. The roots are first attacked, where lesions turn brown or black. As the disease progresses, soft pith in the stem is destroyed, and vascular tissue turns black. Diagnostic symptoms are lodging, black vascular tissue, and the ease with which stems at the base of the plant can be crushed between the fingers. Control is achieved (as for *Fusarium*) by maintaining good growing conditions. Use of drought-tolerant, lodging-resistant, nonsenescing cultivars of sorghum contributes to control.

Milo disease, a rot of root and crown in some genotypes of milos, has been severe in the United States. Susceptibility is determined by a single semidominant gene that mutates to resistance at a fairly high rate. This resistance has been used to provide control.

PANICLE AND SEED DISEASES

Grain molds are an important constraint to sorghum production. Seeds also discolor in wet weather from pigments in the plant, and sprouting of seed in the panicle can occur. There are a number of fungal species that cause molding: *Fusarium moniliforme*, *F. semitectum*, *Curvularia lunata*, *Olpitrichum* spp., *Alternaria* spp., *Helminthosporium* spp., *Phoma sorghina*, and *Colletotrichum graminicola*. *Phoma* appears as small black spots, *Fusarium* as a pink powdery mass that can envelop the seed, and *Curvularia* as a stringy, black, fluffy growth on the seed. Symptoms vary with the pathogenic organism. Control is largely by avoidance; i.e., use of cultivars and/or sowing dates so that grain matures in dry weather. Some cultivars are more resistant to molding than others; some tannins contribute resistance, and flavin-4-ol has been found to contribute. Corneous grains are generally more resistant than floury types. Control of molding is important to grain quality and subsequent uses of the crop. Discolored grain adds unwanted color to products, and severely molded grain does not mill well, resulting in a low starch yield.

Ergot (*Sphacelia sorghi*) is an important disease of sorghum, particularly on male-sterile seed parents in hybrid seed production fields. The disease affects individual florets, interfering with or preventing seed formation. The first sign of ergot is the presence of a sugary, pinkish, syrupy substance that appears in drops coming from infected florets. Severely infected panicles can be almost covered with this sticky syrup. With age the syrup hardens into a white, hard mass, which usually becomes black from saprophytic fungal growth. Under some conditions, a hard irregular cylindrical body protrudes from infected florets. Control is best achieved, particularly for hybrid seed production, by sowing in seasons and locations where infection does not occur, and use of seeds from uninfected crops is beneficial.

Viruses

Eighteen viruses have been reported to infect sorghum—nine only in experimental situations. Viruses cause a number of symptoms: mottling; discoloration (reddening or yellowing); and necrosis of leaves, stems, and peduncles. Stunting, a rosette formation where numerous tillers lie prostrate on or almost on the ground, excessive tillering, and sterility follow infection.

Maize dwarf mosaic virus (MDMV) is found wherever sorghum and johnsongrass occur. Epidemics have occurred in the United States, Europe, Australia, and South America. Maize, broomcorn, millet, and sudangrass are also susceptible. Symptoms include mottling. Symptoms begin with young leaves and spread to older ones. The mosaic appears as chlorotic streaks or dark green islands on a yellow background. A reddish discoloration may appear on leaves, sheaths, and the peduncle. These symptoms tend to disappear if plants grow to reach maturity. Infected plants may be dwarfed. Tillering, head size, and grain number may also be reduced.

The best control is by use of resistant or tolerant cultivars. Destruction of susceptible host plants, johnsongrass for example, contributes.

Sugarcane mosaic virus (SCMV) is a potential problem only where sorghum is grown in the same areas as sugarcane. Many symptoms are similar to MDMV. The disease is aphid-transmitted, and control of aphids offers control of the disease.

Other viruses of potential significance are maize chlorotic dwarf, brome mosaic, maize stripe, sorghum stunt mosaic, sugarcane Fiji disease, and yellow stunt virus.

Nematodes

Nematodes are minute multicellular animals that live in the soil. They are in virtually all of the world's soils. "In general, they are spindle-shaped, colorless, nonsegmented roundworms with complete sensory, digestive, excretory, and reproductive systems" (Frederiksen, 1986).

Nematodes range from 0.4 to 4.0 mm long, averaging about 1 mm, and are 0.01 to 0.05 mm in diameter. Plant nematodes possess a stylet used to pierce host tissue, inject digestive fluids, and withdraw nutrients.

Damage due to nematodes can be difficult to determine. Yield losses ranging up to 10% can go unnoticed. Initially, there can be a decrease in growth and apparent wilted appearance. In more severe situations, areas or patches of a field may show considerably reduced height and vigor than surrounding areas. Another expression is for individual plants scattered at random to be stunted compared with their neighbors.

Control is not easy. It is worthwhile knowing nematode levels in fields of interest, particularly if there have been such problems in the area. If nematodes are below or near a threshold level, crop rotation is recommended, particularly with a crop not susceptible to the same nematode. If nematodes are a problem, avoid transport of soil and plant remains that can infect other areas. Mulching may help reduce nematode populations. There are resistant cultivars, and insecticide-nematicides can be used. Experience of the author indicates that while nematodes are usually not a problem, it is useful to have nematodes checked if plant growth problems are detected. Nematode problems can be anticipated in fields sown repeatedly to sorghum over extended periods of time.

The nematode that has been of greatest concern is *Pratylenchus* spp. (a root-lesion nematode). The two species *P. hexincisus* and *P. zeae* are parasitic on sorghum. Other relevant nematodes are stunt nematodes (*Tylenchorhynchus, Quinisulcius,* and *Merlinius*), root-knot nematodes (*Meloidogyne incognita* and *M. acronea*) and the cereal root-knot nematode (*Meloidogyne naasi*).

Witchweed (*Striga* spp.)

Striga is a parasitic higher plant. The extremely small seed germinates in the presence of a stimulus from the roots of sorghum, pearl millet, or maize. There are a number of species of importance; *S. hermonthica* is found in West Africa eastward into the Sudan and Ethiopia and south around Lake Victoria and northern Namibia. There are two races of *S. asiatica*, a white-flowered type found on the Indian subcontinent and a red-flowered race found from Tanzania southward into South Africa. These are the two most important species, *hermonthica* being more robust, up to 1 m tall, while *asiatica* seldom exceeds 50 cm. *S. forbesii* has been found parasitizing sorghum in relatively restricted areas of Tanzania and Zimbabwe, and *S. densiflora,* found in India, resembles *S. asiatica*.

Striga has already damaged plants before it emerges from the soil. The haustoria of *Striga* penetrate the root and extract nutrients from it. It may also inject substances into the roots toxic to its host. *Striga*-infested plants have symptoms similar to those of drought; leaves wilt and may scorch. *S. hermonthica* may induce chlorotic lesions on the leaves. Infested plants are reduced in height, lighter in stature, have reduced yield, and in cases of heavy infestation, may not produce a head.

This is a serious pest and can be the most limiting factor to yield where it is severe. It is a well-adapted parasite, each plant producing between one and four hundred thousand dustlike seeds that have a 15- to 20-year viability. During underground development, the parasite is completely dependent on the host for nutrients. When it emerges above ground, it is green and there is photosynthesis. *Striga* flowers about 25 to 30 days after emergence. Flowers are lined along stems in leaf axils, being small and white in the Indian species, small and red in the southern African *S. asiatica*, and larger (12 to 15 mm in length) and reddish purple in *S. hermonthica* . Seeds are formed in pods.

Control of *Striga* is difficult. Highly resistant varieties have been developed for the white-flowered *S. asiatica* in India and are being used by farmers. Development of resistance has been promising against the red-flowered species in southern Africa and shown promise in reducing attack of *S. forbesii*. Useful levels of resistance to *S. hermonthica* have also been found, and resistant varieties have found their way onto farmers fields, particularly in the Sudan.

Artificial stimulants to germination, which cause *Striga* to germinate when there are no host plants, have been identified but not found their way to on-farm use. Ethylene was used to control a *Striga* out break in the United States.

There are several trap crops, cotton for example, that germinate the seed but are not infested. If there is a heavy seed load in the soil, the effectiveness of this method of control is limited.

It is beneficial to hand pull *Striga* plants before seed is formed or to control with herbicide. As this is a problem of many traditional farmers, hand pulling is practiced most. *Striga* is generally more severe on fields of low fertility.

On badly infested fields, it may prove necessary for a few years to plant crops that are unaffected, such as cotton, groundnut, and sunflower.

The above discussion of diseases, nematodes, and *Striga* has been taken primarily from the *Compendium of Sorghum Diseases* (Frederiksen, 1986).

INSECT PESTS OF SORGHUM

There are a large number of insects that attack sorghum. The *Sorghum Insect Identification Handbook* (Teetes et al, 1983) lists the following:

- Soil insects: wireworms, white grubs, cutworms, southern corn rootworm, foliage feeders, greenbugs, corn leaf aphid, sugarcane aphid, yellow sugarcane aphid, shoot bug, spittle bug, chinch bug, fall armyworm, oriental armyworm, African (nutgrass) armyworm, red-headed hairy caterpillar, flea beetle, leaf weevil, grasshoppers, migratory locust, banks grass mite
- Stem feeders: shoot fly, spotted stem borer, maize stalk borer, pink borer (Africa), sugarcane borer (Africa), sugarcane borer (Americas), lesser cornstalk borer, sugarcane rootstock weevil
- Head feeders: sorghum midge, bollworm, corn earworm, sorghum webworm, earhead webworm, earhead (Christmas berry) webworm, hairy caterpillar, blister beetle, earhead bug, sap-sucking bug, panicle-feeding bugs, iridescent blue-green cotton bug
- Predators and parasites of sorghum insect pests: ladybird beetle, syrphid fly, common green lacewing, predacious bugs, predacious beetles (ground beetles)
- Insect pests of stored sorghum grains: maize weevil, rice weevil, flat grain beetle, confused flour beetle, lesser grain borer, rice moth, Angoumois grain borer, Indian meal moth

The following comments on sorghum insect pests are summarized from the *Sorghum Insect Identification Handbook* (Teetes et al, 1983). Some of these insects are more important than others and to a degree have broad geographic areas of adaptation. The more important insect pests will be mentioned.

Soil insects attack seeds and seedlings. Wireworms, (several species), white grubs (*Phyllophaga crinita*), and cutworms (several species) are distributed worldwide, whereas the southern corn rootworm is a pest of the Americas. Wireworms feed on seed, destroying the embryo resulting in patches in fields with no plants. White grubs and wireworms feed on young plants destroying roots and cutting the young stem just below the soil surface (cutworms). If plants do not die, growth is stunted and yield reduced. Southern corn rootworm bores into the roots or the base of the stem, destroys the crown, and plants die. Damage from these insects is occasional.

Wireworms can be controlled with seed treatment (heptachlor, lindane, diazinon). Control of the other pests includes crop rotation, plowing six weeks or more before sowing, control of weeds that can be alternate hosts, and use of insecticides.

A number of aphids attack sorghum. The greenbug (*Schizaphis graminum*) is the most destructive. Other aphids include the corn leaf aphid (*Rhopalosiphum maidis*), sugarcane aphid (*Melanaphis sacchari*), and the yellow sugarcane aphid (*Sipha flava*). These are sucking insects; greenbugs attack all leaves, while the sugarcane and yellow sugarcane aphids prefer older leaves. Corn leaf aphids are found in the whorls. Discoloration of leaves occurs where aphids are feeding, and this discoloration expands as the numbers of aphids increase. Toxins are injected into the plants, leaves die, and plants can be stunted, even die. Aphids produce a sticky honeydew that may turn black with time.

Generally, aphid populations are held down by predators. If aphid numbers increase to damaging levels, insecticides can be used; organophosphates are generally effective. In the United States, hybrids with resistance to greenbugs are available. Other than the greenbug, aphids are occasionally a problem, but generally yield is not much reduced.

There are several armyworms, among them the fall armyworm (*Spodoptera frugiperda*), oriental armyworm (*Mythimna separata*), and the African (nutgrass) armyworm (*Spodoptera exempta*). The fall armyworm is an important pest in the southeastern United States and the tropical Americas, where it is frequently an important factor in reducing yield. The oriental army worm occurs throughout Asia, Australia, and New Zealand. This armyworm feeds on leaves, leaving only the midrib, and also attacks panicles. It is a periodic pest, but when insect populations are high, it can devastate the crop. The African armyworm, occurring in East and West Africa, is only occasionally a pest.

There are a number of predators that attack fall and oriental armyworms. Fungus infects the fall armyworm. Insecticides are effective in the control of all three armyworms. Clean cultivation contributes to control.

The chinch bug (*Blissus leucopterus*) is found in North America, where it attacks young sorghum plants. It is a sucking insect, drawing sap from stems and roots. Attacked plant parts redden, and plants become weak and stunted and frequently lodge.

Use of insecticides and barriers against migrating nymphs are the usual control methods. Early planting with a high seed rate into a good seed bed to stimulate rapid growth contributes control.

Shoot fly (*Atherigona soccata*) is an important pest on sorghum in India and Pakistan. It occurs in Africa but at lower levels of severity. It is not found in the Americas or Australia.

Eggs are laid on the lower side of seedling leaves. The maggot hatches and migrates to the growing point, which it kills, and then feeds on decaying tissue. The central leaf wilts and dies and can be pulled from the whorl. Attack occurs in young plants from about one week to one month of age.

Control can be achieved with early sowing. The problem becomes severe with late-sown crops or when it is necessary to resow because first sowings fail due to drought. The use of organophosphates applied in the soil close to the seed, but not in direct contact, will provide reasonable control.

Stem borers are found wherever sorghum and millets are grown. On a worldwide basis, they are the most devastating insect pest. There are a number of stem borers; the spotted stem borer (*Chilo partellus*) is found on the Indian subcontinent and the Far East, and in eastern and southern Africa. This is the most important stem borer in these regions. The maize stalk borer (*Busseola fusca*) is an important stem borer in Africa. There are two species of the pink borer (*Sesamia inferens* and *S. calamistis*), the former widespread in India and Asia, while the latter is found in Africa. The sugarcane borer (*Eldana saccharina*), found in Africa south of the Sahara, is generally not as damaging as the previously mentioned borers. Another sugarcane borer, primarily *Diatraea saccharalis* but including other species, is distributed throughout North, Central, and South America. These borers generally infest sugarcane and maize more than they do sorghum. The lesser cornstalk borer (*Elasmopalpus lignosellus*) is a sporadic pest on sorghum in the Americas.

There are a number of similarities in the damage caused by stem borers. With the exception of the lesser cornstalk borer, which will feed in the roots, feeding occurs in all aboveground parts. There are a number of symptoms: an early symptom is leaf scraping, leaving a transparent window on the lower surface. This tissue dies, and leaves break, giving leaves a ragged appearance. Borers may cut through leaves rolled in the whorl resulting in a row of holes when the leaf grows and unrolls. The growing point may be cut, resulting in a dead heart. Borers tunnel in the stem and the peduncle, which leads to lodging and peduncle breakage. Plant growth is stunted, and when severe, seeds become chaffy.

Destruction of stubble and crop residue is an important factor in stem borer control. A level of resistance has been found for several of the borers, but when attack is heavy substantial damage is done to the crop. Early sowing at a high seed rate followed by destruction of infected plants helps in small fields. A number of insecticides provide control, including organophosphates. Parasites and predators offer some control.

The sorghum midge (*Contarinia sorghicola*) is found in various levels of severity throughout the world where sorghum is grown except Southeast Asia. The midge, a member of the fly family, is 1.3 to 1.6 mm long with an orange red thorax and abdomen. Eggs are laid in flowering spikelets; the maggots feed on and destroy developing seeds, leaving empty florets at maturity. Each female lays eggs in up to 75 florets, and with a large number of flies damage to the crop can be extensive. The fly has an 11-day life cycle and can build up on early flowering varieties or early sown crops and inflict extensive damage on later-flowering sorghum crops.

An effective control can be achieved if the community will sow, preferably an early-maturing cultivar, at the same time. The midge population will then not build up on the first flowering fields and attack later flowering ones. Midge resistant sorghums have been developed in the United States and India. If insecticides are used, repeated application is generally required.

Earhead bugs are serious in parts of India and West Africa. The important head bug in India is *Calocoris angustatus*. Head bugs suck the juice from developing seeds; they then shrivel and discolor, and yield is reduced.

Reasonable control can be realized using an insecticide such as carboryl, first applying about the time of flowering. Open-headed varieties are less attacked than compact headed types. There are predators, but control is modest.

There are several grain-feeding insects including weevils, beetles, and moths. These insects infest a variety of stored grains and flour. The maize and rice weevils (*Sitophilus zeamais* and *S. oryzae*) feed on the seed, frequently leaving pieces of grain. The small flat grain beetle (*Cryptolestes pusillus*) follows the attack of other grain feeding insects feeding on damaged grain. The confused flour beetles (*Tribolium confusum* and *T. castaneum*) are found all over the world, where they attack both grain and stored grain products. The lesser grain borer (*Rhyzopertha dominica*) attacks most cereal grains and flours including those from sorghum and the millets.

The rice (*Corcyra cephalonica*) and Angoumois grain (*Sitotroga cerealella*) moths bore into the grain until they emerge as adults, leaving a characteristic webbing.

Grain should be dry and kept in clean conditions, preferably in insect-proof containers. Fumigation provides control and is available to small farmers in many countries.

Both the adult and nymph of the ladybird beetle (several species of Coccinellidae) effectively feed on aphids and spider mites. The larva of the syrphid fly (several species of Syrphidae) and the common green lacewing (several species of Chrysopidae) are voracious feeders of aphids, mites, and other soft-bodied insects from which they can suck juice. There are several bugs and beetles that feed on sorghum insects and several wasps that develop into adults within the host insect.

DISEASES OF PEARL MILLET

Downy mildew (*Sclerospora graminicola*) is the most important disease of pearl millet. Of second importance is *Striga*, particularly *S. hermonthica* in West Africa. *S. asiatica* also attacks pearl millet. Smut (*Tolyposporium penicillariae*), ergot (*Claviceps fusiformis*), and rust (*Puccinia penniseti*) are widespread on the crop but of less importance. Bacterial and viral diseases occur, but their identity is frequently not known; they are of minor importance. The same is true of nematodes for which not much is known (King, 1992). An estimate of the relative importance of these diseases follows: downy mildew 45%, *Striga* spp. 32%, smut 9%, ergot 7%, rust 3%, viruses, 7% and other diseases 3% (King, 1992).

Downy mildew is widespread in Africa and Asia where the crop is grown, it is somewhat more important in Asia. Virulence differences exist in India and Africa. Systemic infection, streaking of leaves as with sorghum, can occur at any stage of plant growth, but is less likely to appear in the seedling stage. The pearl millet panicle is frequently deformed to various degrees, producing a leafy structure (green ear) (Werder and Manzo, 1992). A large number of sporangia form at temperatures between 15 and 25°C resulting in the white downy appearance on the lower surface of leaf lesions (Balusubramaniam, 1992).

The best method for control is the use of resistant cultivars. Such cultivars have been developed and are in wide use. As for sorghum, the fungicide metalaxyl has been found effective as a seed treatment and to provide relief as a foliar spray. Destruction of infected crop residue and destruction of infected plants in a standing crop contribute to control (King, 1992).

The same species of *Striga* that attack sorghum also infest pearl millet. Contrary to the situation in sorghum, there is no known resistance in pearl millet.

There are four rust pathogens: *Puccinia penniseti, P. substriata* var *indica, P. substriata* var. *penicillariae*, and *P. stenotaphri*. Rust is widespread in Asia and Africa, being moderately important in Asia and of less importance in Sahelian and sub-Sahelian Africa. When the disease occurs, it is generally most severe late in the plants' development so has little impact on yield (King, 1992). Resistance has been identified but has not been transferred to high-yielding cultivars. Inheritance of hypersensitivity appears to be controlled by dominant genes (King, 1992).

Ergot infection first occurs from windblown ascospores arising from sclerotia in the soil. Stigmas are infected, leading to infection of the ovule and the production of a viscous, sticky, sugary liquid. Infected florets do not produce grain but sclerotia that matures with the seed. These sclerotia contain several alkaloids (of the agroclavine group) that are toxic to man and livestock (King, 1992).

In pearl millet, stigmas appear before pollen is shed, the time difference ranging from near simultaneous to three days. One method of control is to have varieties where this difference is small to reduce the time opportunity for infection. An abundance of pollen also contributes. Early sowing may help avoid infection. Other techniques include sowing of sclerotia-free seed and deep plowing to bury sclerotia.

Ergot is a particular problem in the production of hybrid seed because male-sterility in the seed parent increases the time from stigma appearance to pollination. Within a region, it may be possible to find places where infection is minimum or does not occur and use these for seed production.

In the case of smut, soilborne teliospores germinate and produce windborne spores that infect florets. Secondary spread occurs on late-maturing varieties from infected early-maturing types. Infected florets produce top-shaped sori that are somewhat larger than the grain. They are green at first, but turn brown when mature and rupture easily, releasing spores.

Many resistant lines have been bred, resistance appears to be controlled by one or a few dominant genes. Varieties with resistance to ergot are also resistant to smut, but the reverse is not true (King, 1992).

In Zimbabwe, false mildew (*Beniowskia sphaeroidea*) was first observed in the 1985–86 cropping season. Not much is known about the disease, but it does not appear to influence yield much. Resistance to the disease has been found (De Milliano, 1992).

Charcoal rot (*Macrophomina phaseolina*) has been found in lodged plants, but the disease is not severe (De Milliano, 1992).

There are two characteristic viral symptoms, streak and mosaic. These diseases have been found to be severe only occasionally in India, Mali, Nigeria, Niger, and Zambia. Streak viral infection is characterized by intermittent streaking of the leaves, dwarfing, and sometimes excessive tillering. Mosaic symptoms have been associated with dwarfing (King, 1992).

There are some 25 nematodes found on pearl millet, but only three (*Meloidogyne, Pratylenchus*, and *Tylenchorhynchus*) appear to cause any damage. Nematodes in pearl millet are not well understood.

DISEASES OF FINGER MILLET

The most important disease of finger millet is blast, a fungal disease caused by *Pyricularia* spp. Blast is especially severe on the panicles and peduncles, but it also infects other aboveground plant parts. Some resistance is available. This disease is important in India and in East and southern Africa.

Other diseases are Cylindrosporium leaf spot, tar spot, and bacterial blight. Of minor importance are damping off (*Pythium* spp.), foot rot (*Fusarium* sp.), Pyrenophora seedling blight, leaf streak, and some viruslike infections (Adipala, 1992).

INSECT PESTS OF PEARL AND FINGER MILLETS

The insect problems on pearl millet are of less importance than on sorghum. The major problem is from stem borers; this is also true for finger millet. There is a head girdler that produces a spiral-like effect moving lengthwise up the pearl millet head. In some situations, armyworms and aphids can be a problem. The species are essentially the same as on sorghum, and controls are similar (Teetes and Gilstrap, 1988).

Stored grain insects are less severe on pearl and finger millet than on sorghum. Soft grain pearl millet is more subject to attack than hard grain.

CONCLUSION

This chapter was designed to familiarize the reader with sorghum and millet crops. Emphasis has been on quality characteristics, but crop management, cropping systems, and pest problems are also indicated in sufficient detail to provide background information.

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LITERATURE CITED

ADIPALA, E. 1992. Diseases of finger millet in Uganda. In: Sorghum and Millets Diseases: A Second World Review. W. A. De Milliano, R. A. Frederiksen, and G. D. Bengston, eds. Int. Crops Res. Inst. Semi-Arid Tropics (ICRISAT), Patancheru, A. P., India.

ANDREWS, D. J., and KUMAR, K. A. 1992. Pearl millet for food, feed and forage. Advances in Agronomy, Vol. 48, Academic Press.

ANDREWS, D. J., and BRAMEL-COX, P. 1993. Breeding varieties for sustainable crop production in low input dryland agriculture in the tropics. Pages 211-224 in: International Crop Science I. D. R. Buxton, R. Shibles, R. A. Forsberg, B. L. Blad, K. H. Asay, G. M. Paulsen, and R. F. Wilson, eds. Crop Science Society of America, Madison, WI.

AXTELL, J. D., and EJETA, G. 1990. Improving sorghum grain protein quality by breeding. Pages 117-125 in: Proc. Int. Conf. on Sorghum Nutritional Quality. G. Ejeta, E. T. Mertz, L. Rooney, R. Schaffert, J. Yohe, eds. Purdue University, W. Lafayette, Indiana.

AXTELL, J. D., MOHAN, D. P., and CUMMINGS, D. P. 1974. Genetic improvement of biological efficiency and protein quality in sorghum. Proc. Annu. Corn Sorghum Res. Conf. 29.

BALUSUBRAMANIAM, K. A. 1992. Pearl millet diseases in India. In: Sorghum and Millets Diseases: A Second World Review. W. A. J. De Milliano, R. A. Frederiksen, and G. D. Bengston, eds. Int. Crops Res. Inst. Semi-Arid Tropics (ICRISAT), Patancheru, A. P., India.

BHARDWAJ, D. S., SINGH, M., and SATIJA, D. R. 1987. Genetic architecture of quality traits including beta-carotene in pearl millet. India J. Genet. Plant Breed. 47(1):94-98.

BLONDEL, D. 1970. New results on increasing the protein content of the grain of millet (*Pennisetum typhoides*) and sorghum (*Sorghum vulgare*) by nitrogen fertilization in Senegal. Rep. Centre National de Recherches Agronomiques, Bambey, Senegal.

BURTON, G. W., RABSON, R., and AXMANN, H. 1980. Immediate effect on male and female gametes and N on five pearl millet grain characteristics. Crop Sci. 20(1):7-10.

CHAMPIGNY, M. D., BISMUTH, E., and SARDA, C. 1982. Genetic analysis of the relationships between spontaneous and cultivated forms of pearl millet. IV Study of growth and accumulation of starch by the parents and the F1 hybrids obtained by crossing one ecotype of *Pennisetum mollissimum* Hochst (wild species) and a cultivar of *Pennisetum americanum* (L) Leeke. Agronomy 2(4):65-372.

CHAUDHRY, G. A., SORWAR, G. M., and CHEENA, N. M. 1987. Legume-cereal mixture for rainfed areas. Pakistan J. Agric. Res. 8(3):266-269

CHERNEY, J. H., CHERNEY, D. J. R., AKINS, D. E., and AXTELL, J. D. 1991. Potential of Brown-midrib, low lignin mutants for improving forage quality. Adv. Agron. 46:157-198.

DAIBER, R. H. 1971. Grain and malting quality of sorghum cultivars II. 1970 harvest. CSIR Spec. Rep. CHEM 180. Natl. Food Res. Inst. Pretoria, South Africa.

DE MILLIANO, W. A. J. 1992. Pearl millet diseases in southern Africa. In: Sorghum and Millets Diseases: A Second World Review. W. A. J. De Milliano, R. A. Frederiksen, and G. D. Bengston, eds. Int. Crops Res. Inst. Semi-Arid Tropics (ICRISAT), Patancheru, A. P., India.

DEOSTHALE, Y. G., NAGARAJAN, V., and VISWESWAR RAO, K. 1972. Some factors influencing the nutrient composition of sorghum grain. Indian J. Agric. Sci. 42:100-108.

DHOBLE, M. V., BHOSLE, B. R., and KHATING, E. A. 1990. Studies on comparative performance of different intercropping systems under dryland conditions. India J. Agron. 35(4):346-352

DOGGETT, H. 1988. Sorghum, 2nd ed. Longman Scientific and Technical, Harlow, Essex, England

EJETA, G., and AXTELL, J. D. 1987. Dry matter accumulation and carbohydrate composition in developing normal and high lysine sorghums. J. Agric. Food Chem. 35:981-985.

EJETA, G., and AXTELL, J. D. 1990. Development of hard endosperm high lysine sorghum lines. Pages 126-140 in: Proc. Int. Conf. on Sorghum Nutritional Quality. G. Ejeta, E. T. Mertz, L. Rooney, R. Schaffert, J. Yohe, eds. Purdue University, W. Lafayette, Indiana.

EJETA, G., AXTELL, J. D., BUTLER, L. G., and KIRLEIS, A. W. 1989. Proc. Bienn. Grain Sorghum Res. Utilization Conf.,16th, Lubbock, TX.

FREDERIKSEN, R. A., ed. 1986. Compendium of Sorghum Diseases. The American Phytopathological Society, St. Paul, MN.

GANRY, F., and BIDEAU, J. 1974. Effect of nitrogenous fertilization on the yields and nutritional value of a millet, Souma III. Agron. Trop. Nogent. 29:1006-1015.

GARTAN, S. L., TOMER, Y. S., TOMER, R. P. S., and SINGH, M. 1987. Genetics of protein content in pearl millet (*Pennisetum typhoides*) (b). S & H Agric. Sci. Digest. Haryana Agric. Univ. Hissar, India 7(4):188-190.

GODAWAT, S. L., and KAUL, B. K. 1981. Genetic variability in pearl millet. Indian J. Agric. Sci. 51(3):147-149.

GUPTA, V. P., DHILLON, B. S., and SETHI, A. S. 1976. The path analysis of protein, mineral content, and grain yield of pearl millet. Pages 80-85 in: Crop Improvement. Punjab Agric. Univ. Ludhiana, India.

HOUSE L. R. 1978. A Guide to Sorghum Breeding. Int. Crops Res. Inst. Semi-Arid Tropics (ICRISAT), Patancheru, A. P., India.

HULSE, J. H., LAING, E. M., and PEARSON, O. E. 1980. Ch. 3 in: Sorghum and the Millets, Their Composition and Nutritive Value. Academic Press, New York.

ICRISAT. 1992. Annual Report 1991. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, A. P., India.

ICRISAT. 1975–1983. Annual Reports. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, A. P., India.

JACQUES, G. L., VANDERLIP, R. L., and WHITNEY, D. A. 1975. Growth and nutrient accumulation and distribution in grain sorghum I. Dry matter production and Ca and Mg uptake and distribution. Agron. J. 67:607-610.

JACQUES, G. L., VANDERLIP, R. L., and ELLIS, R. 1985. Growth and nutrient accumulation and distribution in grain sorghum II. Zn, Ca, Fe, and Mn uptake and distribution. Agron. J. 67:611-616.

KHANGURA, B. S., GILL, K. S., and PHUL, P. S. 1980. Combining ability analysis beta-carotene, total carotenoids and other grain characteristics in pearl millet. Theor. Appl. Genet. 56:91-96.

KHANNA, M. L. 1966. Composition of bajra (*Pennisetum typhoides*) grain as influenced by fertilization. Indian J. Agron. 11:47-49.

KING, S. B. 1992. World review of pearl millet diseases: Knowledge of future research needs in sorghum and millets diseases. In: Sorghum and Millets Diseases: A Second World Review W. A. J. De Milliano, R. A. Frederiksen, and G. D. Bengston, eds. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, A. P., India.

KRISHNAMURTHY, K. 1968. Nutritive content of ragi varieties in relation to fertilizer levels. J. Nutr. Diet. 5:10-12.

KUMAR, K. A., GUPTA, S. C., and ANDREWS, D. V. 1983. Relationship between nutritional quality characters and grain yield in pearl millet. Crop Sci. 23:232-234.

LIANG, G. H. L., OVERLEY, C. B., and CASADY, A. V. 1969. Interrelations among agronomic characters in grain sorghum (*Sorghum bicolor* Moench). Crop Sci. 9:299-302.

MCKENZIE, H. A., and WALLACE, H. S. 1974. The Kjeldahl determination of nitrogen—A ritical study of digestion conditions—temperature: Catalyst and oxidising agent. Aust. Chem. 7:55-70.

MERTZ, E. T. 1990. Improvement of cereal protein quality through mutations: Historical review. In: Proc. Int. Conf. on Sorghum Nutritional Quality. G. Ejeta, E. T. Mertz, L. Rooney, R. Schaffert, J. Yohe, eds. Purdue University, W. Lafayette, Indiana.

MUKURU, S. Z. 1990. Traditional food grain processing methods in Africa. Pages 216-221 in: Proc. Int. Conf. on Sorghum Nutritional Quality. G. Ejeta, E. T. Mertz, L. Rooney, R. Schaffert, J. Yohe, eds. Purdue University, W. Lafayette, Indiana.

NANDA, G. S., and RAO, N. G. P. 1975. Genetic analysis of some exotic × Indian crosses in sorghum. Nutritional quality and its association with yield. Indian J. Genet. Plant Breed. 35:131-135.

NARWAL, S. S., SINGH, S., MALIK, D. S., and GUPTA, P. C. 1988. Performance and quality of summer cowpea (*Vigna unguiculata* subsp. *cylindrica*), soybean (*Glycine max*) and pearl millet (*Pennisetum glaucum*) grown in mixture and intercropping under different moisture regimes. Indian J. Agric. Sci. 58(11):817-822.

PANDE, P. C., POKHRIYAL, S. C., and SINGH, B. 1985. Heterosis in grain sink activity in pearl millet. Indian J. Genet. Plant Breed. 43(3):409-413.

PRASADA RAO, K. E., DE WET, J. M. J., REDDY, G. V., and MENGESHA, M. H. 1993. Diversity in the samll millets collections at ICRISAT. In: Advances in Small Millets. Oxford and IBH Publ. Co. Pvt. Ltd., New Delhi.

RAI, K. D. 1964. Study of rain-grown sorghum and maize in the central rainlands of the Sudan I. Effect of date of sowing, varieties and spacing on crude protein content and nitrogen accumulation. Indian J. Agron. 9:175-183.

ROONEY, L. W., and MILLER, F. R. 1982. Variation in the structure and kernel characteristic of sorghum. Pages 145-162 in: Proc. Int. Symp. on Sorghum Grain Quality. L. W. Rooney and D. S. Murty, eds. Int. Crops Res. Inst. Semi-Arid Tropics (ICRISAT), Patancheru, A. P., India.

SACHDEVA, A. K. 1981. Genetics of yield and some quality traits in pearl millet (*Pennisetum typhoides* (Burm.) Stapf and Hubb.) (Abstr.) Thesis Abstr. 7(1):77-78. Harayana Agric Univ., Hissar, India.

SAWHNEY, S. K., and NAIK, M. S. 1969. Amino acid composition of protein fractions of pearl millet and the effect of nitrogen fertilization on its proteins. Indian J. Genet. Plant Breed. 29:395-406.

SHUKLA, U. C., and BHATIA, K. N. 1971. Effect of nitrogen levels on the Fe and Mn concentrations and uptake in hybrid and local varieties of pearl millet (*Pennisetum typhoides* (Burm. F.) Stapf & C. E. Hubb.) Indian J. Agric. Sci. 41:790-794.

SIDDESWARAN, K, RAMASWAMY, S., and MORACHARAN, Y. B. 1989. Nutrient uptake of finger millet as influenced by intercrops, border crops and N fertilization. Madras Agric. J. 76(7):361-365.

SINGH, P., and GUPTA, V. P. 1987. Combining ability for grain quality traits in pearl millet. Indian J. Genet. Plant Breed 47(2):141-144.

SINGH, R., and AXTELL, J. D. 1973. High lysine mutant gene (hl) that improves protein quality and biological value of grain sorghum. Crop Sci. 13:535-539.

STABURSVIK, A., and HEIDE, O. M. 1974. Protein content and amino acid spectrum of finger millet (*Eleusine corocana* (L.) Gaertn) as influenced by nitrogen and sulfur fertilizers. Plant Soil 41:549- 571.

STUTZEL, H., and VANDERLIP, R. L. 1988. Grain yield of intercropped sorghum and pearl millet as influenced by sorghum genotype and cropping pattern. J. Agron. Crop Sci. 160(3):191-197.

SULLIVAN, T. W., DOUGLASS, J. H., ANDREWS, D. J., BOND, P. L., HEMCOCK, J. D., BRAMEL-COX, P. J., STEGMEIR, W. D., and BRETHOUR, J. R. 1990. Nutritional value of pearl millet for food and feed. Pages 83-94 in: Proc. Int. Conf. on Sorghum Nutritional Quality. G. Ejeta, E. T. Mertz, L. Rooney, R. Schaffert, J. Yohe, eds. Purdue University, W. Lafayette, Indiana.

SWINDALE, L. D. 1979. Proc. Int. Workshop on Intercropping, Hyderabad, India. Int. Crops Res. Inst. Semi-Arid Tropics (ICRISAT), Patancheru, A. P., India.

TEETES, G. L., and GILSTRAP, F. E. 1988. Development and evaluation of systems for controlling insect pests of sorghum/millet by integration of resistant varieties, cultural manipulation and biological control. Annu. Rep. INTSORMIL, University of Nebraska, Lincoln.

TEETES, G. L., REDDY, SESHU, K. V., LEUSCHNER, K., and HOUSE, L. R. 1983. Sorghum Insect Identification Handbook. Inf. Bull. 12. Int. Crops Res. Inst. Semi-Arid Tropics (ICRISAT), Patancheru, A. P., India.

TOMER, P. S. 1970. Test weights and protein content in bajra in relation to methods of sowing, manurial treatments and seed rates. Ann. Arid Zone 9:159-162.

TYAGI, C. S., and PARODA, R. S. 1982. Genetic analysis of protein content in pearl millet. Indian J. Agric. Sci. 52(11):718-722.

VANDERLIP, R. L. 1979. How a sorghum plant develops. Kans. Agric. Exp. Stn. Contr. 1203.

VENKATARAMANA, R. S., and KRISHNA RAO, D. V. 1961. Chemical composition and nutrient uptake of ragi J. Indian Soc. Soil Sci. 9:245-252.

WAGGLE, D. H., DEYOE, C. W., and SMITH, F. W. 1967. Effect of nitrogen fertilization on the amino acid composition and distribution in sorghum grain. Crop Sci. 7:367-368.

WARSI, A. S., and WRIGHT, B. C. 1973. Effects of rates and methods of nitrogen application on the quality of sorghum grain. Indian J. Agric. Sci. 43:722-726.

WERDER, J., and MANZO, S. K. 1992. Pearl millet diseases in western Africa. In: Sorghum and Millets Diseases: A Second World Review. W. A. De Milliano, R. A. Frederiksen, and G. D. Bengston, eds. Int. Crops Res. Inst. Semi-Arid Tropics (ICRISAT), Patancheru, A. P., India.