PEARL MILLET FOR FOOD, FEED, AND FORAGE

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I. INTRODUCTION

Pearl millet [*Pennisetum glaucum* (L.) R. Br.] is widely grown as a food crop in subsistence agriculture in Africa and on the Indian subcontinent on a total of about 26 million ha (Rachie and Majudar, 1980) where grain yields average 500–600 kg/ha. Relatively little is grown (mostly as a forage crop) in intensive agriculture in other continents. Pearl millet has a number of advantages that have made it the traditional staple cereal crop in subsistence or low-resource agriculture in hot semiarid regions like the West African Sahel and Rajasthan in northwestern India. These advantages include tolerance to drought, heat, and leached acid sandy soils with very low clay and organic matter content. However, it has the ability to grow rapidly in response to brief periods of favorable conditions—a feature of such semiarid tropical regions. In ideal conditions, it has one of the highest growth rates of all cereals (Kassam and Kowal, 1975; Craufurd and Bidinger, 1989) (Fig. 1). Its grain is generally superior to sorghum as human food and at least equals maize in value as a feed grain. Whereas grain is the main purpose of cultivation in Africa and Asia, the forage, or stover, at harvest is an important secondary product in subsistence agriculture for animal feed, fuel, or construction. Thus vigorous tall or semitall relatively late varieties with a high biomass production are preferred. High-yielding, early semidwarf hybrids are grown in India on about 30% of the cultivated area; however, lower biomass production and unstable disease resistance have limited their spread.

Two principal types of food are traditionally made from pearl millet—porridges and flat unleavened breads. Both of these are made from flour; however, because pearl millet flour deteriorates after a few days and acquires a "mousy" odor, fresh flour must be ground frequently. Other products include rice-like foods made from pearled grain, couscous, foods from blends with legume flour, and beer.

Pearl millet gives a productive pasture for grazing, especially with dwarf varieties, and silage is easily made. Several cuts can be taken. Although pearl millet does not produce a cyanogenic glucoside like dhurrin in sorghum, it is a strong nitrogen accumulator and can produce potentially toxic levels of nitrates if not well managed. Pearl millet is used as a forage crop in the United States, Australia, and southern Africa, but the hybrid with elephant grass (napier grass), *P. purpureum* Schum., is widely used as a perennial forage crop in east and southern Africa, Brazil, and India where it is principally propagated by cuttings.

Several of the attributes that made pearl millet the best adapted food cereal for the stressful production conditions of West African Sahel are valuable for developing a combine feed grain crop for intensive cultivation

Figure 1. Crop of pearl millet grain variety Ex Bornu at Samaru, Nigeria, producing 22 t/ha above-ground dry matter in 90 days, of which 3.2 t (14.5%) was grain.

in warm-temperate regions. Principal of these is a high growth rate, which confers excellent response to increases in soil fertility. Under ideal conditions, grain yields of 3.5–8 t/ha have been obtained in India from early hybrids maturing in 85 days (Burton *et al.*, 1972). Other factors include an enormous range of genetic variability already collected but largely unused in the primary germplasm pool of the species, from which traits of major importance are still being identified. Existing characteristics, which are already being used in developing combine phenotypes, are major dwarfing genes, maturity control, through both photoperiodicity and independent maturity genes, and high levels of tolerance to heat and moisture stress. Several systems of cytoplasmic-genic male sterility are available to exploit well-manifested hybrid vigor. Though good yields are possible from varieties, typically 20-30% more grain yield can be expected from a hybrid of the same maturity class. Pearl millet grain crops can, when properly dry, be harvested with sorghum equipment. Grain test weights are about 10% higher than those for sorghum, and feeding tests show that pearl millet grain is generally slightly superior to sorghum in feed value, particularly for poultry. The better feed value is due to lower levels of polyphenols without tannins, higher protein levels with a slightly better amino acid profile, and 3–6% oil providing an increased energy content. Experimental dwarf combine hybrids have been recently developed in the United States. These hybrids can produce a grain crop in a temperate summer season as short as that in Carrington, North Dakota (Andrews and Rajewski, 1991).

II. THE PLANT

A. DESCRIPTION AND ORIGIN OF PEARL MILLET

Pearl millet has had a varied taxonomic history. It is currently again known as *Pennisetum glaucum* (L.) R. Br. (USDA, 1986; IBPGR, 1987) but was variously classified as *P. americanum* (L.) Leeke, *P. typhoides* Stapf. and Hubb., and *P. glaucum* (Brunken, 1977; de Wet, 1987). The position of the cross-fertile wild and weedy relatives that were previously given different specific names remains unclear. Since *glaucum* has been adopted at the species level, and if the attributions of Brunken (1977) are followed, then the weedy subspecies become *P. glaucum* ssp. *stenostachyum* and the wild subspecies *P. glaucum* ssp. *monodii*. Common names include bulrush or cattail millet and mil aux chandelles. In Africa, gero, maiwa, souna, dukhn, and sanio and in India bajra and cumbu are a few of many names.

Pearl millet is an annual tillering diploid ($2n = 14$), highly cross-pollinating cereal. Three gene pools have been recognized in respect of pearl millet (Harlan and de Wet, 1971). The primary pool contains cultivated, wild, and weedy pearl millets (above) which interbreed freely. The secondary pool contains only elephant grass, *P. purpureum* ($2n = 28$). This species can be crossed with pearl millet but although there is some homology between the pearl millet genome and the A′ genome of elephant grass (Hanna, 1987, 1990), the progeny are sterile unless the chromosome number is artificially doubled. This interspecific cross can also be achieved by first doubling pearl millet, which will reproduce at the tetraploid level. The tertiary gene pool contains numerous distantly related *Pennisetum* species with various ploidy levels that do not naturally interbreed with the primary pool. Each pool has potential for the improvement of cultivated pearl millet. The primary pool has an enormous range of variability (Kumar and Appa Rao, 1987), but this has been inadequately evaluated and even less used. Important genes for forage quality, disease resistance, and male sterility systems have been recently recognized. The interspecific cross between pearl millet and elephant grass is widely used in the tropics as a vegetatively propagated multicut perennial forage. Elephant grass contributes perenniality, drought and disease resistance, and high biomass production to this cross while pearl millet improves forage quality and palatability. This interspecific cross has been used to derive genes for fertility restoration, stiff stalk, maturity, and height from the A′ *purpureum* genome (Hanna, 1990) and is also of potential importance in accessing traits from the tertiary gene pool. Dujardin and Hanna (1989, 1990) have shown that the *P. glaucum* × *purpureum* hybrid can be used as a genetic bridge to make crosses with species such as *P. squamulatum*, a source of apomixis, which cannot be crossed directly with pearl millet.

Pearl millet was probably domesticated in Africa in the savannah south of the Sahara and west of the Nile possibly 5000 years ago (Brunken *et al.*, 1977; Porteres, 1976). Domestication involved relatively few gene changes (Bilquez and LeComte, 1969; Marchais and Tostain, 1985). The crop subsequently spread to east and southern Africa, and about 3000 years ago to the Indian subcontinent. It is generally agreed that the ancestral type for pearl millet resembled *P. violaceum* (a race of ssp. *monodii*, according to Brunken, 1977), which is still currently distributed on the southern fringes of the Sahara (Fig. 2). This concept of domestication, developed from

Figure 2. Wild pearl millet *Pennisetum glaucum* ssp. *monodii* (syn. *P. violaceum*), Northern Niger. (Courtesy S. Tostain.)

archeological, ecological, morphological, cross-compatability and genetic studies, is supported by relationships based on isozyme and restriction fragment length polymorphism (RFLP) analyses (Tostain *et al.*, 1987; Gepts and Clegg, 1989; Tostain and Marchais, 1989) and protein fractions (Chanda and Matta, 1990). Possibly there were several domestication events (Porteres, 1976; Tostain and Marchais, 1987).

A great range of diversity has developed, particularly in west and central Africa, which has been collected, maintained, and partly classified by ICRISAT in conjunction with IBPGR. The World Collection of pearl millet and some of its wild and weedy relatives now stands at 22,000 accessions. It is generally believed that wild relatives of pearl millet continue to intercross with cultivated varieties in west and central Africa to form hybrid swarms, part of which, called "shibras," mimic and survive in the host cultivar (Fig. 3). However, recent research indicates the presence of barriers that restrict but do not entirely prevent gene flow between the wild and the cultivated species (Robert *et al.*, 1991). Although the shibras are a nuisance to the farmer because their grain shatters, the ongoing genetic

Figure 3. Variability in a farmer's pearl millet crop, Bankass, Mali, including a weedy segregant (a shibra—taller plant with many thin heads, back right.)

transfer from the wild and weedy types since domestication has probably been of much evolutionary value in terms of adaptation and stability of production of the cultivated crop in the long term. A similar situation has been described in sorghum (Doggett and Majisu, 1968). Bramel-Cox *et al.* (1986) showed that progeny derived from crosses of pearl millet cultivars × wild or weedy species had higher growth rates than those from cultivated × cultivated crosses.

Since time of maturation is an important factor in the adaptation of tropical cereals, particularly in respect to yield and quality, flowering in almost all pearl millet landrace varieties is retarded by long days and induced by short days (Burton, 1965a; Ong and Everard, 1979). This photoperoid sensitivity, which differs minutely between cultivars, permits flowering and, hence, grain maturation to coincide with the time when the season usually ends each year, largely irrespective of the date of planting. Bilquez (1963) classed pearl millet varieties as either facultative (flowering occurs but is delayed by long days) or obligate (only flowers when short days occur).

Photoperoid response is one of many environmental factors that are of critical importance in the utilization of pearl millet germplasm and in the characterization of many traits. Whereas a few important traits, such as grain color, are relatively independent of environmental effects many others, such as grain and forage yield and quality, are strongly affected. Variation in the period of time between seedling emergence and floral initiation obviously has a large influence on performance in both grain and forage varieties (Craufurd and Bidinger, 1988, 1989). It is essential, therefore, to recognize the effect of environment both in breeding and in the assessment of quality values.

The relationship between pearl millet and sorghum [*Sorghum bicolor* (L.) Moench] is relevant when discussing the existing adaptation and potential use of pearl millet for food, feed, and forage in both tropical and warm-temperate agriculture. Sorghum was also domesticated in Africa and is widely grown as a food cereal there and in other semiarid regions that are similar to those where pearl millet is dominant but with more ensured rainfall and better soils. The interface between the adaptation zones of the two crops in Africa is, however, not all that distinct. There are a few specialized sorghums adapted to the drought stress and heat peaks at seedling establishment and floral development that characterize the zone where pearl millet is the dominant cereal. In contrast, there are many millet cultivars of both long and short duration found where sorghum is the predominant food cereal. They are used together to stabilize food supply over varied soil types and unpredictable rainfall regimes. Indeed short-season millet and long-season sorghum are common traditional intercrops in Nigeria, which more efficiently utilizes season-long resources (Andrews, 1972; Andrews and Kassam, 1976).

Despite the similarity between pearl millet and sorghum in terms of adaptation and use as food, and though both crops were introduced into the United States in the last century and used as forage crops, pearl millet has not been developed into a feed grain crop, as sorghum was in a process that commenced around the 1930s (Duncan *et al.*, 1991). The reason for this is not clear, but it may initially have been because mutants, especially for reduced plant stature, are easier to extract and multiply in sorghum, a largely self-pollinated species, than in pearl millet. Following the success of hybrid development in India, and the realization that pearl millet generally has a more nutritious grain than sorghum, breeding pearl millet for feed grain production has commenced in the United States.

B. BREEDING

Pearl millet is a naturally cross-pollinating species in which traditional cultivars are random-mating populations with considerable internal variability. As much as 30% inbreeding depression may occur in these after one generation of selfing (Khadr and El-Rouby, 1978; Rai *et al.*, 1984).

The floral biology of pearl millet permits many breeding techniques to be used, ranging from various types of population improvement to strict pedigree selection. Pearl millet is protogynous and the interval between the emergence of all stigmas and anthesis on one head may extend from 1 to 6 days (Fig. 4). This facilitates natural cross-pollination, but bagging emerging heads allows easily controlled crossing or selfing. Each head produces 500 to 1500 seeds and, depending on density, one plant may produce many heads.

Good levels of heterosis are expressed in pearl millet. Typically a single-cross hybrid between two inbred parent lines yields 20–30% higher than an adapted variety of comparable maturity, though much higher levels have been reported in the literature (Rachie and Majmudar, 1980; Kumar, 1987). Good line × variety hybrids can also be made. Though inbreeding depression is significant, productive inbred lines can be selected with sufficiently high seed yields so that three-way crosses are not economically necessary for hybrid seed production.

Several cytoplasmic–genic male sterility (cms) systems are available in pearl millet (Kumar and Andrews, 1984; Hanna, 1989). The release of the first and currently the most widely used source, Tift23A_1 from Tifton, Georgia, in 1965 (Burton, 1958, 1965b) permitted forage hybrids to be developed in the United States and grain hybrids to be widely grown in India.

The possibility of using protogyny to make grain hybrids in pearl millet is being investigated (Andrews, 1990). This method allows quicker hybrid

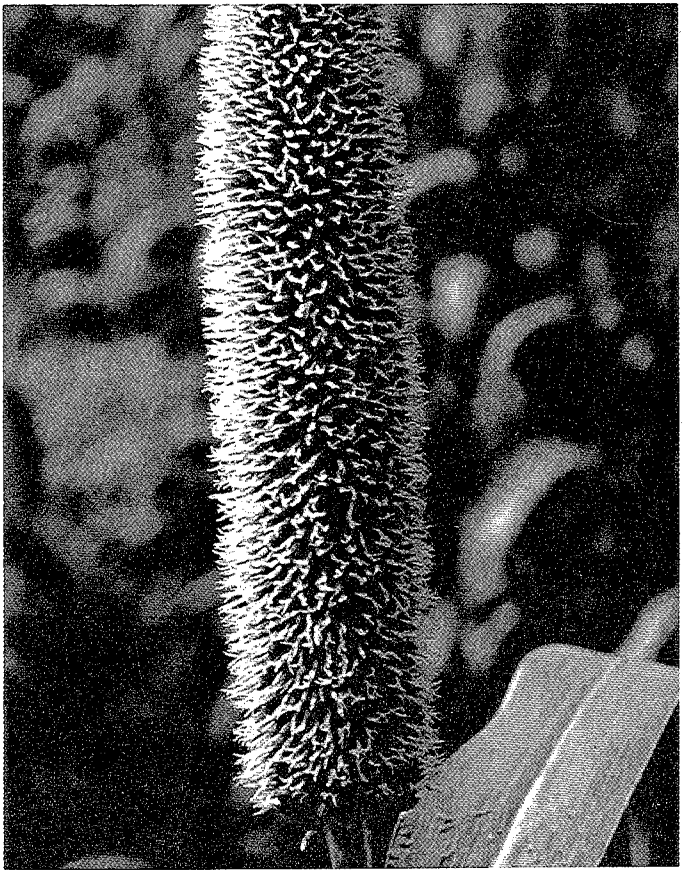

Figure 4. Complete protogyny in a pearl millet head.

development, is less restrictive of the range of parental combinations possible, and avoids diseases that are associated with the use of cms seed parents, particularly in Africa, where these hybrids, especially of the topcross type, would be of most utility. Some "seed parent" selfing may occur when making hybrid seed by protogyny. Tests with mechanical mixtures of seed parent and hybrid seed showed that up to 20% of seed from an inbred female parent had no significant effect on hybrid performance, provided the hybrid has a dominant phenotype (Andrews, 1990). The use of a variety as a male parent reduces female parent selfing through a profuse and prolonged pollen supply and confers some of the stability of performance characteristic of varieties into the resulting topcross hybrid.

The development of forage cultivars in the United States in the past 50 years (see Table II) has progressed from open-pollinated varieties, through synthetic varieties and polycross F_1's, to single-cross hybrids. Advances have been made in both biomass productivity and digestibility, the latter largely through the use of dwarfing genes to increase leaf/stem ratio. Tolerance to nematodes and diseases has been incorporated.

Most of the breeding for grain production in pearl millet has so far been done in India, although the cytoplasm used to produce all Indian hybrids derives from Tift23A_1.The longevity of individual hybrids in India until recently has been short, 3–5 years, because of the instability of their resistance to pearl millet downy mildew, a disease that is not known in the New World. The Indian hybrids, though their yield potential is high, are semidwarf, 1.3–1.8 m, and do not possess the persistent stem strength needed for mechanical harvesting. Many are also partly photosensitive, and thus mature too late when planted more than about 30° latitude from the equator (Bidinger and Rai, 1989). New phenotypes are, therefore, required for use in the U.S. Midwest. These phenotypes should be non-photoperiod-sensitive and early to very early with sufficient stalk and peduncle strength and with an upright tiller habit to confer lodging resistance that will persist after frost. Experimental hybrids approaching the required phenotypes have been produced in Nebraska (Andrews, 1990) (Fig. 5) and Kansas (Christensen *et al.*, 1984; Stegmeier, 1990) and have been jointly tested, with hybrids from Tifton, Georgia, in 1988–1990 regional tests. Test locations (years) have been in Mississippi State, Mississippi (1); Tifton, Georgia (2); Hays, Kansas (3); Lincoln and Sidney, Nebraska (3); Lafayette, Indiana (3); and Carrington, North Dakota (1). Mean location yields ranged from 2300 to 3800 kg/ha. Across tests, the best millet hybrids averaged 85% of sorghum check yields; however, in locations where the season was short as in North Dakota and in double-cropping after wheat in Indiana, millet yields exceeded those of sorghum. Similar results were obtained earlier in western Kansas (Christensen *et al.*, 1984) here the highest experimental millet grain yield was 5300 kg/ha.

C. BIOTECHNOLOGY

The term "biotechnology" encompasses several applications to manipulate genetic material—ranging from incorporation of desired genes into plants and use of DNA markers such as RFLPs to select desirable genes to the determination of genetic relationships and the production of superior individuals. Tanksley *et al.* (1989) suggested that integration of RFLP techniques into plant breeding would (*a*) hasten the movement of desirable

Figure 5. Dwarf pearl millet grain hybrid in regional test, Sidney, Nebraska.

genes among varieties; (*b*) permit transfer of genes from related wild species; (*c*) allow analysis of complex polygenic characters as groups of single Medelian factors; and (*d*) establish genetic relationships between sexually incompatible crops plants.

Smith *et al.* (1989) identified 64 RFLP markers linked to genes of 26 plant traits in elephant grass, most of which are quantitative in nature. The RFLP markers were linked to genes affecting *in vitro* organic matter digestibility (IVODM), neutral detergent fiber, and nitrogen and phosphorous concentration. In addition to RFLP analysis, a newer technique, random amplified polymorphic DNA (RAPD), that relies on polymerase chain reaction (PCR) appears to be more promising in applied breeding programs, as it is quicker and eliminates several tedious steps that are involved in the RFLP technique (Williams *et al.*, 1990; Welsh and McClelland, 1990).

In a practical breeding program, DNA markers would allow the definitive identification of plants carrying a recessive gene in segregating populations independent of evironment. In addition, establishment of correlations between quantitative trait loci (QTL) of interest and specific RFLP markers allows selection of specific chromosome segments affecting a quantitative trait from a population of plants and incorporation into single plants with high efficiency (Helentjaris and Burr, 1989). In pearl millet, specific areas where these techniques could be used would include selection for complex traits such as drought and disease resistance and forage quality attributes. A random genomic probe library in pearl millet is now available (R. L. Smith, 1991, personal communication) and could be used to establish linkages between QTL and RFLP markers. To take advantage of the new technologies available and achieve desired goals, close cooperation among biotechnologists, plant breeders, and agronomists is essential.

D. CONSUMER QUALITY AND YIELD

Pearl millet is principally grown for human food in the drier tropical regions of the world where agricultural production is at most risk from pest, disease, and highly variable weather conditions. Farmers have, therefore, historically selected their varieties for consistency of production in the face of the occurrence of stress caused by drought and low soil fertility and for resistance to pests, birds, and storage insects, as well as for characteristics associated with food preparation and organoleptic qualities. For characteristics that are associated with these objectives, compromises have resulted. For instance, harder grain (more vitreous endosperm) is associated with resistance to damage from storage insects, whereas for many food products a softer endosperm would be better. In blind preparation or tasting tests the most widely grown local variety is usually rated as acceptable, but it may not be the most preferred (this has consequences both for the breeder and for the interpretation of consumer test results without reference to cultivar performance). Additionally, nutritional quality values as such have not been selected for traditional agriculture, only in as much as they are associated with some other evidently desirable trait. However, research into the genetic variability present in germplasm resources of pearl millet has revealed a wide range of values for traits affecting nutritional quality. In consequence, where variability is demonstrated, the probability of further improving nutritional quality traits in pearl millet through breeding exists. A relevant example is that of protein and lysine levels. Variability for protein content was demonstrated in pearl millet genotypes by Kumar *et al.* (1983). Selection resulted in inbreds with higher protein levels. Lysine in protein percentage declined, but there was still a net increase in lysine per sample. This contributed to a higher protein efficiency ratio, and thus an increase in total nutritional value as determined by rat-feeding tests (Singh *et al.*, 1987). Hybrids made between these inbreds and normal parents showed some elevation in protein level (ICRISAT, 1984), indicating partial dominance for the expression of protein content.

A review of information on the nutritional status of humans in the West African Sahel (IDRC, 1981) concluded that there are seasonal energy deficiencies, accentuated in women by the additional labor needed to find fuel and prepare food, protein-energy deficiencies in 20–30% of the children, and nutritional anemia in 40% of the children and up to 60% of the women. The latter had many causes—including deficiencies in iron, folic acid, vitamin B_{12}, and protein. Annegers (1973) had earlier noted that the nutritional status of the population in West Africa primarily dependent on pearl millet was better than that of people mainly using sorghum, maize, or rice. Many socioeconomic factors contribute to malnutrition, but higher and more stable cereal production levels, more protein (vegetable and animal), and dietary education are needed.

In a nutritional survey in south Indian villages, in a sorghum-, pearl-, millet-, and rice-growing area, Ryan *et* al. (1984) noted calorie and vitamin deficiences especially among rice eaters. They concluded that the prime need was more energy supply and that breeding for increased protein content or quality of cereals should not be undertaken if it would hinder progress for yield. Protein and vitamins could more easily be obtained by other means.

E. GRAIN CHARACTERISTICS

1. Physical

Pearl millet grain is about one-third the size of sorghum (Fig. 6) and 100 grain weights range from 0.5 g to over 2.0 g. While average grain weights of common cultivars vary greatly in different regions, over about 1.0 g/100 is normally acceptable; however, it appears feasible to breed for slightly larger grain without sacrificing yield potential. Grain shape can vary considerably from globular to lanceolate (IBPGR, 1981) where the length-to-width ratio ranges from equality to nearly 4:1. Long thin grains are the result of a high grain number relative to the surface area of the panicle, and thus are usually angular in cross section. Grain of such shapes are harder to

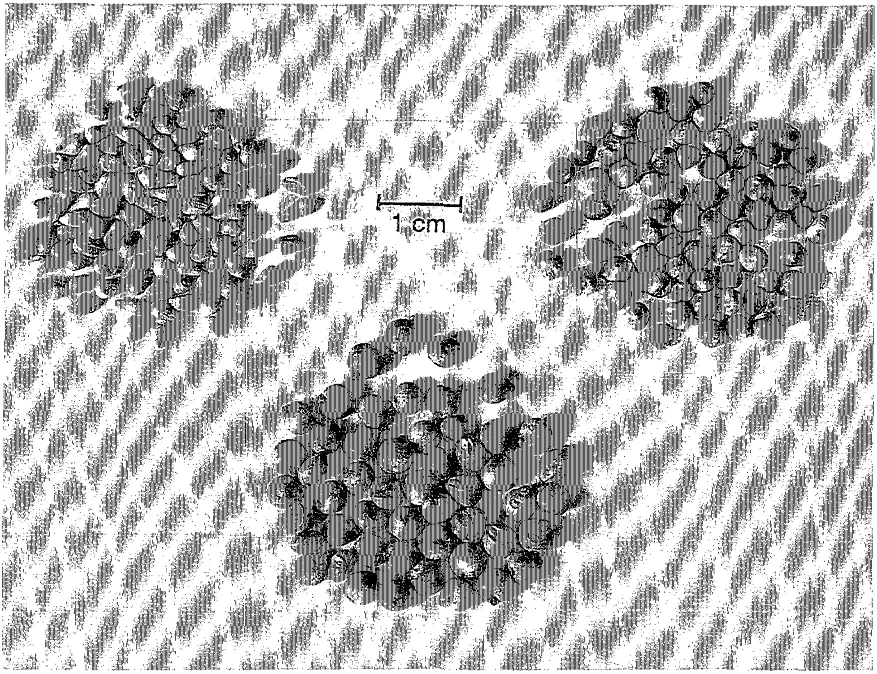

Figure 6. Pearl millet grain. (Left) Cream/white cultivar; (right) large gray-grained cultivar; (bottom) red-grained sorghum.

decorticate and give lower flour yields. Grain color in pearl millet is a combination of the color and thickness of the pericarp, particularly the mesocarp, and the color and vitreosity of the endosperm. Colors are creamy-white to yellow, light to dark brown, various shades of light to dark blue/gray, and purple. Sunlight causes the lighter colors to fade and humid conditions during grain ripening dull the color of the grain through superficial mold and bacterial infection in the pericarp.

The slate gray color in pearl millet is due to the presence of flavonoids (Reichert, 1979), which can be present in both the pericarp and the peripheral endosperm. While no condensed tannins have been found in pearl millet (Hulse *et al.*, 1980; Reichert *et al.*, 1979), such as those that interfere with protein utilization in sorghum, differences in total phenol content have been detected (McDonough and Rooney, 1985) with bronze (brown) seeds having higher levels than yellow or blue gray. The slate gray color in millet product is pH dependent (Reichert and Youngs, 1979) and can be reduced by using acidic additives such as tamarind extract, or sour milk during food preparation.

Pearl millet grain averages 75% endosperm, 17% germ, and 8% bran (Abdelrahman and Hoseney, 1984) (Fig. 7). The proportion of germ in pearl millet is thus about twice that of sorghum, which is a factor contributing to the higher nutritive value of pearl millet grain. The germ is firmly embedded in the endosperm and may not be completely removed by milling.

The pericarp is composed of three layers of different cell structures (Figs. 7 and 8). The epicarp has one or two layers of thick cubic cells with a thin layer of cutin on the outer surface. The epicarp is most important in resisting "weather" damage (Sullins and Rooney, 1977). The mesocarp may vary in thickness, being composed of one to several layers of cells that collapse at maturity. Pericarps with thin mesocarps are more translucent and allow the endosperm color and texture to show through. The term "pearl" in pearl millet is derived from the glistening appearance of unblemished grains with a translucent pericarp and vitreous endosperm. The innermost component of the pericarp is the endocarp composed of both cross and tube cells below which is the outer layer of endosperm aleurone cells, which may be pigmented. On decortication the bran, which is composed of all three layers of the pericarp, is reported to separate from the endosperm either above or below the layer of the aleurone cells (McDonough and Rooney, 1989). This difference is attributed to the method of decortication and is important because the aleurone layer is relatively rich in protein and vitamins. Thick pericarp varieties better resist superficial

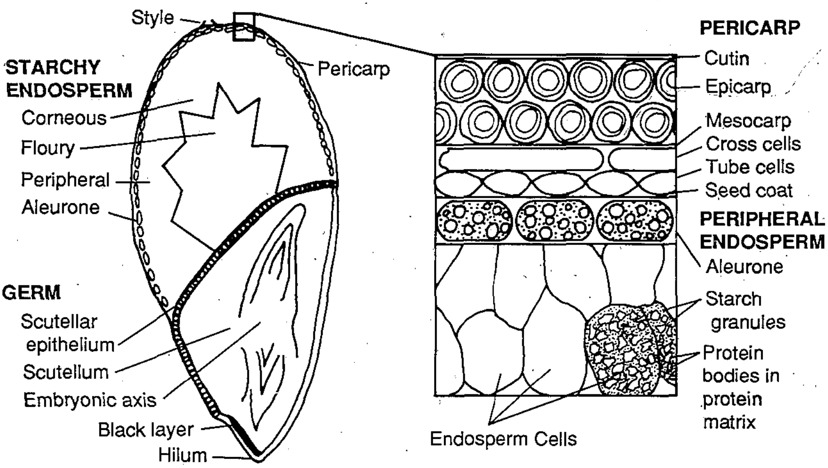

Figure 7. Diagram of longitudinal section of pearl millet grain. Modified from Rooney and McDonough (1987); reproduced with permission from the publisher.

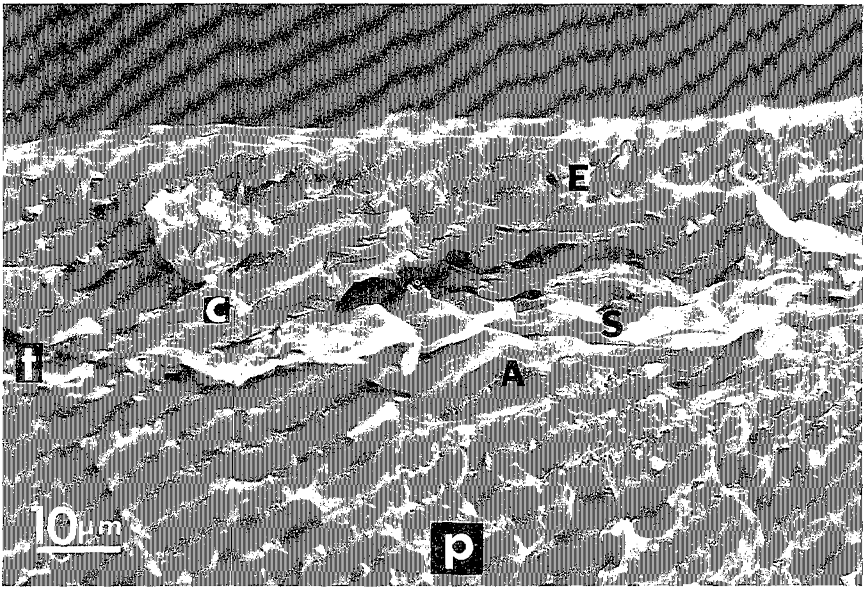

Figure 8. SEM micrograph of pearl millet pericarp and peripheral endosperm. e, epicarp cells; c, cross cells; t, tube cells; s, seed coat; a, aleurone; p, peripheral endopserm. Reproduced with permission from ICRISAT (see Rooney and McDonough, 1987).

mold damage in moist conditions and may be easier to decorticate (Kante *et al.*, 1984).

Three parts to the starchy endosperm, which may vary in proportion in different varieties and which all contribute to the flour, are recognized by Rooney and McDonough (1987). The peripheral region contains many protein bodies, in a matrix surrounding small starch granules. Below that is a corneous layer in which large, uniform-size starch granules are closely packed in a protein matrix with a few protein bodies. The innermost part is the floury endosperm with loose large round starch granules in a thin protein matrix with a few protein bodies. The flour consists of free starch granules from the floury endosperm and pieces of the other two parts. The fineness of these pieces determines quality in many food products where there is not adequate time given in preparation to soften these pieces. Indeed this may be a contributory reason why products such as the porridges are left to ferment or stand overnight before consumption. Bread made from wheat flour extended with pearl millet flour may be noticeably gritty unless the millet is milled very finely (Hoseney, 1988).

2. Composition

The averages of proximate analyses conducted on pearl millet indicate a protein content of about 12%, carbohydrates 69%, lipids 5%, fiber and ash around 2.5% each, and the remainder being moisture (Rooney ad McDonough, 1987; Hoseney *et al.*, 1987; Hulse *et al.*, 1980). However, considerable ranges—especially in protein content, from 8 to 24% (Hulse *et al.*, 1980; Rooney and McDonough, 1987), and lipids, from 3.0 to 7.4% (Hoseney, *et al.*, 1987)—have been reported (Table I). It is likely, however, that in normal germplasm protein levels much over 18% are caused by partial grain development or derived from unusually low yielding sources—weak inbred lines or where seed-set was incomplete. Kumar *et al.* (1983) indicate that grain protein level is subject to strong environmental effects. Several authors conclude (Burton *et al.*, 1972; Rooney and McDonough, 1987; Hoseney *et al.*, 1987) that pearl millet tends to have a higher mean protein level than sorghum grown under similar conditions. In pearl millet variety trials grown at three locations in the U.S. Midwest, grain protein levels in pearl millet average 10.6%, whereas the sorghum checks recorded 9.5% (Andrews, 1990). However, protein levels of 12 to 14% are commonly reported for grain pearl millet grown in the Midwest (Walker, 1987).

The fatty acid composition of the free and bound lipids in pearl millet and sorghum are quite similar (Rooney, 1978) but the total level is considerably higher in pearl millet, 3 to 7%, a factor that contributes to the higher calorific values of pearl millet.

The amino acid profile of pearl millet is better than that of normal sorghum and normal maize and is comparable to the small grains such as wheat, barley, and rice (Ejeta *et al.*, 1987) with less disparate leucine/isoleucine ratio (Hoseney *et al.*, 1987; Rooney ad McDonough, 1987). The percentage of lysine in protein as reported in pearl millet ranges from 1.9 to 3.9 g/100 g protein (Ejeta *et al.*, 1987; Hoseney *et al.*, 1987).

Despite analytical surveys of the World Collection by ICRISAT, mutants have not been discovered in pearl millet where, as in sorghum, maize, and barley, the lysine content of grain protein is substantially increased by the action of major genes. Although it appears possible through selection to increase grain protein content, percentage lysine in protein decreases at higher grain protein levels, though percentage lysine in the sample still increases (Kumar *et al.*, 1983). Additionally, as grain yields are increased generally grain protein content declines, though, as with lysine content, net protein yield per hectare increases. Pearl millet contains a lower proportion of cross-linked prolamins which are slightly

Table I

Protein Content and Essential Amino Acid Composition of Pearl Millet and Sorghum Grains[a,b]

	Pearl Millet					Sorghum			
Amino acids	No. of samples	Range (g 16 g^{-1} N)	Mean (g 16 g^{-1} N)	Amino acid score[c]	Pattern[d] (g 16 g^{-1} N)	No. of samples	Range (g 16 g^{-1} N)	Mean (g 16 g^{-1} N)	Amino acid score
Lysine	280	1.59–3.80	2.84	52	5.5	412	1.06–3.64	2.09	38
Threonine	29	3.17–5.66	4.07	102	4.0	29	2.12–3.94	3.21	80
Valine	29	4.38–7.67	6.01	120	5.0	29	3.84–6.93	5.40	108
Methionine + cystine	29	1.43–3.96	2.71	77	3.5	24	1.80–2.69	2.36	67
Isoleucine	29	3.70–6.34	4.56	114	4.0	29	2.85–5.05	4.17	104
Leucine	29	8.62–14.80	12.42	177	7.0	29	10.12–17.60	14.67	210
Phenylalanine + tyrosine	29	6.54–10.81	8.49	142	6.0	29	6.11–10.72	8.87	148
Protein (%)	280	6.40–24.25	12.30			412	4.60–20.25	11.98	

[a] Determined by ion exchange chromotography.

[b] Adapted from Jambunathan *et al.* (1984) *in* Rooney and McDonough (1987). Reprinted with permission from the publisher (see ICRISAT, 1987).

[c] Percentage of recommended pattern.

[d] From FAO/WHO (1973), p. 67.

higher in lysine and tryptophan content than sorghum (Jambunathan and Subramanian, 1988), which may be an additional factor contributing to the higher digestability of pearl millet proteins (Hoseney *et al.*, 1987). Yellow endosperm has been reported in pearl millet (Curtis *et al.*, 1966), but although its carotene content was about the same (1.0–0.2 ppm) as that for yellow sorghum, it is low compared to that for yellow maize.

Pearl millet appears to be generally free of any major antinutritional factors, such as the condensed tannins in sorghum which reduce protein availability. As with other cereals, pearl millet contains phytic and nicotinic acids mainly in the germ (Simwemba *et al.*, 1984; McDonough, 1986). Two trypsin inhibitors have been reported in pearl millet (Chandrasekhar and Pattabiraman, 1981). Osman and Fatah (1981) reported that in western Sudan, where iodine intake is low, goiter in humans was associated with high millet as against wheat-based diets. Klopfenstein *et al.* (1983, 1985) showed that in rats thyroid hormones were affected, but that symptoms could be alleviated by dietary adjustments.

III. FOOD PRODUCTS

A range of food products with numerous local names (Appa Rao, 1987; Sautier and O'Deyes, 1989) are made from pearl millet, which are well described by Hulse *et al.* (1980), Hoseney *et al.* (1987), Rooney and McDonough (1987), and Serna-Saldivar *et al.* (1990).

The major types of food are (*a*) porridges, either thick or thin, which are common in Africa and (*b*) flat bread, either unfermented (mostly Asian) or fermented (Ethiopia and Sudan). Other products are couscous, boiled rice-like preparations, snacks from blends with legume flours, and non-fermented or fermented beverages in Africa.

All these products are made from either coarsely or finely ground millet flour (the degree of fineness is often important) usually with separation and removal of the bran. A major constraint with the utilization of pearl millet is the propensity of the flour (or damaged grain) to acquire a mousy rancid odor within a few days of milling, which is accentuated when water is used to temper the grain before milling. This odor was previously attributed to enzymatic degradation of grain lipids (Chaudhary and Kapoor, 1984) but subsequently Reddy *et al* (1986) have shown that it is associated with apigenin, a flavanoid compound in the usual blue/gray pigmentation in pearl millet. However, varieties with white or cream-colored grain also give the mousy odor, but to a lesser extent. It is probably that both oxidation of lipids and apigenin contribute to the "off"-odors in pearl millet. Dry milling or heat treatment after milling produces a flour with a longer shelf life.

In general there are less-pronounced cultivar preferences in pearl millet than there are in sorghum. However, consumers prefer lighter colored rather than darker pearl millet foods. This is achieved through a combination of grain type, degree of decortication, and change in pH during preparation. Reichert *et al.* (1979) showed that the pigments of gray or yellow-gray grain varieties are easily bleached by traditional methods of lowering pH, whereas pigments of yellow, brown, or purple are not. Since some pigments are located in the external layers of the endosperm, decortication is often excessive in traditional methods to remove these pigmented layers, which reduces both the extraction rate and the nutritive value of the flour.

A. PORRIDGES

Porridges are made in both India and Africa, and a variety of methods are used. Rooney and McDonough (1987) describe the preparation steps in detail for the more widely used types.

Thick porridges or pastes known as "tô" or "tuwo" in West Africa are generally solid enough to be broken into convenient pieces for eating and dipped in a stew or sauce. Since thick porridges are normally eaten with the fingers, it is important that there be sufficient gelatinization of the starch to prevent crumbling, but not enough to make it too sticky and therefore difficult to handle. Although genotype has some effect, the most important factors are the fineness to which the flour is ground and the preparation technique, which involves cooking part of the flour first to get a thin well-gelatinized liquid and then adding the remaining flour and cooking further to get the correct consistency. Both alkaline and acid porridges may be made. In some preparations, the flour may be soaked overnight with sour milk or fermented briefly, before cooking.

Thin porridges, or gruels, are made to be drunk or eaten with utensils. In Nigeria, the whole grain may be steeped for 2 or 3 days in water before it is crushed and its bran removed. This allows the germination process to begin (but not to the stage of malting) with resultant changes in the endosperm and germ. The process, which involves further fermentation and decanting before cooking, produes a smooth-textured porridge with a preferred sour taste. Germination and fermentation have been shown to improve nutritional value through improved protein quality and digestibility and increased vitamin content (Serna-Saldivar *et al.*, 1990).

B. Flat Breads

Roti, a flat unleavened bread, is the usual way in which pearl millet and other grains such as sorghum and maize are eaten on the Indian subcontinent. This type of unleavened bread is uncommon in Africa, but fermented breads are used on both continents. Roti can be made from whole millet flour, without separation of the bran, simply with the addition of warm water. In India, flour is traditionally ground between rotating or reciprocating stones, which can grind more finely than the wooden mortar and pestle used in Africa (though in Africa saddlestones may also be used). In both regions, of course, motor-driven plate or hammer mills are now commonplace at the village level, but preferences for characteristics in food products change slowly. In roti, particularly, fineness of the flour is most important. Pearl millet, as is the case with other tropical cereals, has no gluten, and cohesiveness of the dough is dependent on the surface tension between particles, which, when the correct amount of water is used, is greatest as particle size decreases (Olewik *et al.*, 1984). The dough for roti should be capable of being flattened by hand into a disk 1–3 mm thick and 12–25 cm in diameter, and after cooking briefly (about 2 min, including turning) at a high temperature, it should, if kept in a covered container, retain flexibility for several hours.

To make fermented breads—galettes of West Africa, kisra of Sudan and Ethiopia, and dosai of India—the flour is first mixed with water and a starter and left to ferment for 12 to 24 hr and then cooked quickly at a high temperature on a metal sheet or in a clay oven. For kisra, just before cooking, sufficient water is added to make a very runny paste that can be spread very thinly. For dosai bean flour up to one-third of the total may be added before fermenting.

C. Other Traditional Foods

Couscous or "arraw" is a steamed product made by gelatinizing and agglomerating pearl millet flour with additives that may include sugar and mucilaginous gums from okra or baobab. Steaming prevents off-odors from forming and couscous is one of the few products that stores well and can be conveniently prepared by rehydrating with milk or steam. The drawback with couscous is that it is complicated and energy-expensive to prepare.

Idli is a steamed product made in India, usually for breakfast, from a fermented mixture of pearl millet and legume flour.

D. TRADITIONAL PROCESSING

The processes of fermenting, malting, and brewing (below) each increase nutritive value relative to the direct use of unprocessed flour.

1. Fermenting and Malting

Fermenting without prior malting, hydrolyzes starch, softens flour particles, and lowers the pH, which helps bleach the flour, and slightly increases protein digestibility (Hemanalini *et al.*, 1980).

Malting (germination) begins the process of mobilizing seed reserves, both starch and protein, and initiating shoot and root growth. The vitamin content of the grain is improved and the levels of lipids, phytates, and oxalates are lowered (Opoku *et al.*, 1981). Intrinsic grain enzymes improve protein quality and digestibility and increase the availability of free sugars, B-vitamins, and ascorbic acid (Hamad and Fields, 1979; Aliya and Geervani, 1981). Brewing continues the biochemical processes commenced in malting, on both the malt and any other starch base which may be added, assisted by enzymatic activity of lactobacilli and yeasts which may be present or added in a starter kept from previous brewings. The microorganisms continue to improve protein and vitamin availability (Hulse *et al.*, 1980; Novellie, 1982). Pearl millet malt is made in the usual way, germinating the grain by keeping it moist, warm, and aerated. At the correct time the germination process is halted and the grain sun-dried and ground. The diastatic activity was found to be the highest 32 hr after germination (Jain and Date, 1975). Apart from brewing, the malt may be used, together with legume flour in other preparations of value as weaning food and for pregnant women and for convalescent people.

2. Brewing

Beers are important nutritional adjuncts to the diets of people who are principally cereal dependent, as the malting and brewing processes increase bioavailability and vitamin contents. Beer production is common throughout Africa and any cereal that is locally available may be used, though sorghum is perhaps most widely used. Sorghum varieties preferred for brewing have moderate but not high tannin levels and produce a malt with high diastatic power. Pearl millet does not have tannins and in eastern and southern Africa malt from finger millet (*Eleusine coracana* Gaertn.) may be used as an additive to provide the bitter taste and increase diastatic levels. Both lactobacilli, which contribute the acid sour taste through the formation of lactic acid, and wild yeasts are involved in fermentation

(Doggett, 1988). Temperatures used during the stages of brewing are important in controlling the activity of the enzymes and organisms (Rooney and McDonough, 1987). Two types of beer are made: a sour opaque alcoholic beverage that is still fermenting when consumed and a clear sweet or slightly sour beer.

E. NEW PROCESSES AND NEW FOODS

Ease of food preparation is becoming a more important consideration in communities dependent on subsistence agriculture. Compared with the alternatives of preparing food from sorghum, wheat flour, or rice, which store longer, pearl millet flour, which needs to be prepared from grain (which itself has to be threshed, as pearl millet is usually stored at on the head in household granaries) every few days, is a less attractive prospect. This may be one of the reasons why the area cultivated with pearl millet has declined by about 1% a year in India over the last 20 years and has remained static in Africa despite increases in population. More knowledge about the causes of rancidity is obviously needed, to determine what genetic variation may exist and whether economically viable processing control methods can be developed.

A major source of nutrient loss is in decortication. Excessive decortication reduces extraction rates and lowers nutritive value of the flour, since protein and vitamin levels are higher at the periphery of the endosperm. Manual decortication methods are highly variable, depending on the operator and utensils, and in general give extraction rates of 70 to 80%, which are lower than those obtained with mechanical means. The main drawback to manual methods, however, is the time and effort involved (Eastman, 1980). Varietal differences have been linked to ease of decortication (Kante *et al.*, 1984) and grain shape also affects extraction rates, with nearly sperical grains being best (Rooney and McDonough, 1987). Plate and hammer mills are now commonly being used at the village level, and, for the same extraction rates, little difference in flour nutrient levels between manual and mechanical methods was observed (Reichert and Youngs, 1977).

The most effective and easily controlled method of decortication is an abrasion process, as in the Tangential Abrasion Decortication Device (TADD) developed by IDRC (Reichert *et al.*, 1986) for village level use. Either batch or continuous flow versions are available. Akingbala (1991) noted while studying pigments distributed mainly in the pericarp of pearl millet grain, that 8% decortication by dry milling with the TADD dehuller was equal to 20% by traditional methods in terms of pigment removal.

The traditional method of making couscous from coursely or finely milled flour is a protracted and skilled process and involves a relatively high amount of fuel. A standardized batch process involving a V-blender of making "arraw," a form of Senegalese couscous with sugar, has been developed by Walker (1987). This should reduce product cost and make couscous an available food of a more uniform quality.

Blending up to 20% pearl millet flour with wheat flour has been shown to be practical (Dendy *et al.*, 1970; Sautier and O'Deyes, 1989) and acceptable to consumers in Senegal and the Sudan (Perten, 1983). Fine milling of pearl millet flour is necessary to avoid a gritty texture in the bread. Blending has not been widely adopted, however, as imported subsidized wheat is cheaper and of a more consistent quality than pearl millet at the flour mill gate.

After decortication, whole or broken pearl millet grain can be used in rice-like preparations in Africa and India. Rooney (1989), while researching ways that this might be done on a large scale, found that decortication was easier and resulted in less loss if the grain was first parboiled and slowly dried. The pearled parboiled grain can be easily cooked and produces a rice-like product called "milri." Cream or yellow varieties of pearl millet make the most attractive milri. Parboiling gives good control of the development of off-odors and thus prolongs shelf life. Recent work (S. D. Serna-Saldivar, C. Clegg, and L. W. Rooney, 1991, personal communications) show that only slight differences exist in chemical composition and nutritional value of parboiled and raw grains decorticated to the same extent. In either case 17.5% decortication increased protein and dry matter digestibilities. Milri, therefore, appears to meet several of the requirements of a new food from pearl millet—it can be produced in bulk, it stores better, and food is easily prepared from it.

Germination and malting increase the food value of cereal grains, and additions of legume flour and vitamins can produce a balanced weaning food (Malleshi and Desikachar, 1986). Badi *et al.* (1990) compared pearl millet- and sorghum-based baby foods each made from 70% flour, 13% malt, and 17% milk powder. The use of part of the cereal as malt lowered the viscosity of the foods as well as slightly improving digestibility. There were no differences in energy values but the pearl millet food contained 20% more protein and was considered to provide adequate protein and energy levels for 9-month-old children, whereas the sorghum food would provide sufficient levels for 1-year-old children. Almedia-Dominguez *et al.* (1990a) described the production by extrustion or puffing of baby food from 70% pearl millet and 30% cowpea flour, which supplied 17, 72, and 110%, respectively, of the daily needs of protein, lysine, and threonine of a

2-year-old child. Extrusion of moist pearl millet flour at 200–240° C greatly increased water solubility and would be suitable for preparing snack foods (Almeida-Dominguez *et al.*, 1990b).

IV. PEARL MILLET GRAIN AS FEED

Though pearl millet is grown only for its forage in the United States, it has the potential to be used like maize and sorghum in rations of poultry, swine, and beef cattle (Hanna *et al.*, 1991).

A. POULTRY FEEDS

Research on formulation of poultry feeds using pearl millet has been carried out to ease competition for energy sources between humans and monogastrics and reduce feed costs. Studies conducted by several workers (French, 1948; Singh and Barsaul, 1976; Sharma *et al.*, 1979) have shown that millets compared favorably with maize in poultry diets. Fancher *et al.* (1987) reported that the metabolizable energy (ME_n) content of ground pearl millet varied from 2.891 to 3.204 kcal g^{-1} dry matter, depending on the cultivar, and suggested that previously reported ME_n values for pearl millet were underestimated by up to 21%.

French (1948) included up to 60% pearl millet or white seeded finger millet in layer's diets without any reduction in egg production. Sanford *et al.* (1973) found that at equal levels, the amino acid profile, rate of chick gain, and efficiency of utilization of feed were favorable for pearl millet compared with sorghum grain as a source of energy and protein for broiler-strain chicks.

Lloyd (1964) observed that broilers fed on millet rations were heavier and had better feed conversion than those fed on maize rations. No significant differences were found between the diets in slaughter weights and yields and both were equivalent in the production of good quality carcasses. However, it was noted that millet-fed carcasses had a slightly higher pigmentation than those fed on maize. Abate and Gomez (1983/1984) partly substituted maize with pearl millet and finger millet in both broiler starter and finisher feeds. The chicks fed on pearl millet diets had highest overall body weight gain and finger millet was comparable to maize. They also showed that in broiler diets pearl millet could effectively replace part of the vegetable protein supplement provided the diet was supplemented with up to 0.3% lysine.

Smith *et al.* (1989) conducted trials with pearl millet, grain sorghum, and triticale substituting each grain for 50 or 100% of maize in the control diet. Pearl millet and grain sorghum replaced maize in the diet of chicks without adversely affecting gain or feed efficiency. They concluded that an economic assessment of dietary treatments would be premature because no fair market price or established production practices exist for pearl millet in the United States.

Sullivan *et al.* (1990) reported three chick-feeding tests conducted in Nebraska and Kansas. In each test, chick growth rates were similar on diets containing pearl millet, low-tannin sorghum, and maize. High-tannin sorghum gave lower growth rates. Pearl millet had higher ME_n values. In 1989, when pearl millet was produced in the same field as the sorghum, the crude protein content of the pearl millet grain was 0.9 to 1.7% points higher than that of sorghum varieties.

The studies reviewed indicate that pearl millet, if properly supplemented with protein sources, could be used in poultry feeds as an energy source. The protein in pearl millet grain provides all essential amino acids except lysine. The decision to use pearl millet in poultry feeds is primarily one of economics, as feeds would still require, as for maize, some added protein or essential amino acids from more expensive ingredients.

The potential of dehydrated and pelleted pearl millet forage has been explored in the United States (Wilkinson *et al.*, 1968). Wilkinson and Barbee (1968) reported that dehydrated products of coastal Bermuda grass and pearl millet compared favorably in metabolizable energy values to dehydrated alfalfa and can be used as adjuncts to dehydrated alfalfa in supplying supplementary xanthophyll in poultry feeds. Butler *et al.* (1969) observed that millet can be dehydrated and pelleted at ages up to 45 days, despite the high proportion of large-diameter stems, and that it can be processed in to a high-quality feed additive. The potential of dehydrated forage for use as an ancillary to dehydrated alfalfa in supplying supplementary xanthophyll in poultry feeds needs further investigations.

B. BEEF CATTLE

Studies at Fort Hays, Kansas, have shown that finishing steers on pearl millet diet gained as well as those fed sorghum (Christensen *et al.*, 1984). Compared to sorghum grain, pearl millet grain had higher levels of both fat and protein and the protein had a better balance of essential amino acids. Estimated net energy of millet was 4% higher than that of finely rolled sorghum. Steers gained 1.32 kg/day on pearl millet compared to 1.26 kg/day on sorghum. Pearl millet grain used with Rumensin in growing rations for calves gave significantly higher gains that sorghum. The authors concluded that pearl millet grain is an excellent source of protein for beef cattle rations. Preliminary results from Zimbabwe (S. C. Gupta, personal communication) indicate that sorghum and pearl millet could be used as high-energy substitutes for maize in pen-fattening diets of steers.

In a metabolism trial with six steers, Hill and Hanna (1990) found that apparent digestibility of dry matter (DM), organic matter, and dietary total digestible nutrients were higher for the control, 73% maize + 6% soybean meal (C), than for 76.2% grain sorghum + 2.8% soybean meal (GS) or 79% pearl millet (PM) diets. Ether extract and crude protein digestibilities were higher for C and PM than GS and retained nitrogen level was similar for all three diets. In a growth trial with yearling heifers, they observed higher average daily gain on C compared with PM; however, feed:gain ratios were similar for all three diets (8.2, 9.1, and 8.5 kg feed/kg gain, respectively).

C. Pigs

Calder (1955, 1961) reported that for pig feeding the millet grains should be finely ground so that the risk of internal irritation caused by the hard hull of the grain is reduced to a minimum. Pigs fed ad libitum on diets containing 75 and 50% pearl millet reached the average slaughter weight of 90.8 kg 10 days earlier than the maize control group. His experiments established that pearl millet has high value for pig feeding. Pearl millet promoted the formation of firm white fat comparable to that resulting from barley feed.

Pearl millet could also be used for grazing by pigs to save on concentrates. Burton (1980) reported that 45.5-kg pigs on full feed of a balanced concentrate grazed young pearl millet (var. Tifleaf 1) for 35 days, gained as well as those in dry lot, and required less concentrate per kilogram of gain. The concentrate saved by grazing made the pearl millet crop worth $250 per hectare.

D. Sheep

There are not many reports on the use of pearl millet grain and forage in the feeding of sheep. French (1948) observed that whole grains of pearl millet fed to sheep were less digested and a fair percentage passed whole into the feces. He suggested that grinding the grain can bring its feeding value nearly to that of crushed maize.

Martinez (1988) allowed lambs 4, 6, 9, or 12 kg herbage/100 kg live weight. Average live weight gains per lamb were 65, 68, 90, and 100 g/day respectively, corresponding to live weight gains of 663, 478, 434, and 374 kg/ha. A 6- to 7-kg allowance gave a reasonable balance between live weight gain per lamb and carrying capacity per hectare.

V. PEARL MILLET FORAGE

A. Varieties and Hybrids for Forage

Pearl millet varieties and hybrids with improved forage production potential have been developed and released for use in the United States and Australia. A list of the varieties and hybrids released for forage production is found in Table II. Recent varieties and hybrids furnish good summer grazing for milk cows and all classes of livestock; give a desirable seasonal distribution of forage; and are suitable for green chop, dehydration, pelleting, and production of quality silage.

In the development of new varieties and hybrids, two major genes, *d*, and *tr*, have been used in the improvement of forage quality (Burton, 1983). Increases in the proportion of leaf, and thus the nutritive value of the forage, are obtained by the use of the d_2, dwarfing gene which reduces internode length and therefore plant height by 50%. It is inherited as a simple recessive gene (Burton and Fortson, 1966; Burton *et al.*, 1969; Johnson *et al.*, 1968). Because of higher leaf proportion, forage from dwarf plants is higher in IVDMD than forage from tall plants. Johnson *et al.* (1968) observed that though the dwarf millets produce less dry matter per hectare they have 50% more leaves, 15% more protein, and 17% less lignin, and animal gains were more than those from tall millet. The trichomeless (*tr*) gene suppresses trichomes on all plant parts and is inherited as a single recessive gene (Powell and Burton, 1971). Though the *tr* gene increases forage palatability for cattle, because of a lower number of cracks on the adaxial and abaxial leaf surfaces, penetration of rumen microbes is reduced, resulting in slower digestion and thus reduced intake (Hanna and Akin, 1978). The loss in IVDMD associated with the *tr* gene tends to be compensated for by associated drought tolerance and better palatability (Burton *et al.*, 1977, 1988).

The brown-midrib (*bmr*) trait in pearl millet has potential to contribute to increased digestibility, as it is associated with reduced lignin concentration and increased IVDMD (Cherney *et al.*, 1988). Using wether sheep,

Table II

Pearl Millet Varieties and Hybrids for Forage Production

Designation	Type	Developed from	Main attributes (reference)
		Australia	
Katherine Pearl	Variety	An introduction from Ghana	Tall, late maturing, provides "wet season" grazing during growth and a standover forage for dry season (CSIRO, 1972)
Tamworth	Variety	Selection made following of a F_3 plant of Gahi 1	Mid-season to late in maturity, tillers well, suitable for summer/autumn grazing (CSIRO, 1972)
Ingrid Pearl	Variety	Introduction from Bambey, Senegal	Earlier than Katherine Pearl
		United States	
Starr	Synthetic	Crossing a leafy short plant discovered in Russian introductions with broadleafed and palatable "common" millet	Percentage and yield of leaves higher, good for fattening cattle (Burton and DeVane, 1951)
Gahi 1	Hybrid	Mixture of about 75% of 6 possible hybrids from 4 inbreds and 25% selfed and sibbed seed of these inbreds	Leafier, more forage, better seasonal distribution (Burton, 1962)
Gahi 2	Hybrid	Same as Gahi 1, except 4 different dwarf inbreds used; hybrid is tall	Produced less forage than Gahi 1 (Burton and Powell, 1968)
Tiflate	Synthetic	54 short-day photoperiod-sensitive introductions from West Africa	Remains vegetative much longer, better distribution of forage than Gahi 1, higher leaf and percentage IVDMD than Gahi 1 (Burton, 1972)
Gahi 3	Hybrid	cms Tift23A (or Tift23DA) × inbred Tift186	Matures later than Gahi 1, provides grazing for longer period, immune to *Pyricularia*, resistant to nematodes (Burton, 1977)
Tifleaf 1	Hybrid	cms Tift23DA × inbred Tift383	Easier to manage, matures later than Gahi 1, provides grazing for longer period, immune to *Pyricularia*, resistant to nematodes (Burton, 1980)
Tifleaf 2	Hybrid	cm Tift85D_2A × inbred Tift383	Resistant to rust and *Pyricularia*, better performance than Tifleaf 1 under rust infection (Hanna *et al.*, 1988)

Cherney *et al.* (1990) reported that the digestibility of DM, neutral detergent fiber, and acid detergent fiber were uniformly higher in the *bmr* genotype than in the normal, and lambs spent an average of 2.6 min on *bmr* genotype for every minute spent on the normal genotype, indicating its good palatability. The orange node trait (*on*) controlled by a single recessive gene resembles the *bmr* trait. The earhead, stem and leaf sheath were more digestible in the *onon* plants than normal plants and leaf blade digestibility did not differ. Results from crosses between *on* × *bmr* indicated that they were affected by the same gene (Degenhart *et al.*, 1991).

Burton (1962) demonstrated the potential of heterosis for forage production with the four-parent hybrid Gahi 1. Gahi 1 is a mixture of approximately 75% of the six possible hybrids from four inbred lines and 25% of selfed and sibbed seed of these lines. The hybrid seedlings, being more vigorous than their selfed parents, crowd out the inbreds and usually give yields comparable to 100% hybrid seed (Burton 1948, 1989). Gahi 3, a hybrid between the cms Tift23DA (or Tift23A) and inbred Tift186, eliminates this problem of mixtures of hybrid and selfed seed (Burton, 1977). In the production of cms forage hybrids, male parents (pollinators) that fail to restore fertility of the F_1, hybrid are preferred because they reduce the weed potential of the hybrid and improve forage quality, provide longer grazing, and yield under stress (Burton, 1981).

In Australia, improved varieties have potential for wet-season grazing during growth, as stand-over mature forage for the dry season, and in the production of palatable silage. In South Africa, pearl millet is called "Babala" and is used for summer grazing by cows and is also valued as a silage crop because it usually yields better than other silage crops (Penzhorn and Lesch, 1965; Hammes, 1972). In Korea, recent research has indicated that pearl millet has excellent potential as a forage crop (Choi *et al.*, 1990a). A pearl millet hybrid "Chungaecho" (Tift23DA × Tift186 = Gahi 3) was recently recommended to livestock farmers following extensive evaluations (Choi *et al.*, 1990b). Pearl millet is also being advocated for use as pasture in Brazil (Coser and Maraschin, 1983; Moraes and Maraschin, 1988). Breeding for forage yields per se has not received any attention in India and West Africa. Local varieties are dual purpose—provide both grain and dry fodder (Rachie and Majmudar, 1980). Forage breeding in India has concentrated on the interspecific hybrid between pearl millet and elephant grass (Gupta and Sidhu, 1972).

B. Diseases and Forage Production

Diseases are usually of minor importance where pearl millet is grown for forage. The initial growth is generally free from diseases but forage production from the second growth late in the season is affected by them (Burton, 1951). Diseases when severe cause substantial reductions in forage quantity and quality by lowering the protein content, acceptability, and digestibility (Burton, 1954; Burton and Wells, 1981).

Rust caused by *Puccinia substriata* var. *indica* was recognized as a serious disease on late-planted pearl millet following outbreaks in the southeastern Great Plains in the United States in 1972 (Wells *et al.*, 1973). The effects of rust are very severe and range from death of young plants from early infection to premature desiccation and or death of leaves with later infection.

Comparisons of rust-resistant and -susceptible plants showed significant reductions in DM concentration, DM yield, and IVDMD in diseased plants (Monson *et al.*, 1986). The combined effect of lower yields and lower IVDMD led to a mean 51% reduction in IVDMD from the infected plants. The yield of leaves was reduced less by rust than was the yield of stems, but the opposite was true for IVDMD concentrations. In contrast to the results of Monson *et al.* (1986), Wilson *et al.* (1991) did not observe an effect on DM concentration and this was explained to have resulted from differences in stages of harvest. They have observed a decrease in DM yield and digestibility with increased rust infection. Their results suggested that rapid loss of digestible DM yield at low rust severities represents a loss from the more highly digestible leaves.

The rust situation has been admirably managed by breeding varieties and male-sterile lines that are resistant to rust—an important step in maintaining forage quality. Andrews *et al.* (1985) identified a single dominant gene (*Rpp*$_1$) for rust resistance in an accession from Chad. Hanna *et al.* (1985) reported that a single dominant gene (*Rr*$_1$) controlled rust resistance in *P. americanum* subsp. *monodii* from Senegal, which was transferred to pearl millet by backcrossing.

Leaf spots caused by *Bipolaris* (*Cochliobolus*) *setariae, Cercospora penniseti, Helminthosporium stenospilum, Phyllosticta penicillariae*, and *Pyricularia grisea* (*Magnaporthe grisea*) generally appear after pearl millet flowers (Luttrell, 1954; Hanna and Wells, 1989; Wells and Hanna, 1988; Wilson *et al.*, 1989). Burton and Wells (1981) estimated that *Cercospora* leaf spot when severe reduced forage yields by 20–25% and brown mottle (unknown etiology) had no effect on the first forage yield, but reduced the second harvest by 23% and the third by 30%. Resistance to *B. setariae* leaf spot is controlled by a four-independent gene system (Wells and Hanna, 1988) and to *P. grisea* by three independent and dominant genes (Hanna and Wells, 1989).

Insect pests that infest pearl millet include the fall armyworm, *Spodoptera frugiperda*, larvae of the corn earworm *Heliothis zea*, the lesser cornstalk borer (*Elasmopalpus lignosellus*), and chinch bugs (*Blissus leucopterus leucopterus*). Lines resistant to fall armyworm and chinch bug have been identified (Leuck *et al.*, 1968; Merkle *et al.*, 1983). Pearl millet suffers rare infestations by the lesion nematode (*Pratylenchus* spp.) and sting nematode (*Belonolaimus* sp.). New varieties carry resistance to these nematodes (Burton, 1977).

C. MANAGEMENT FOR FORAGE

Since Voorhees (1907) first described management practices for obtaining palatable forage from pearl millet in the United States, several studies have been carried out on the management of this crop for grazing and forage. These essentially include experiments on intensity of grazing and frequency, number and height of clipping on quality, and interaction between stubble height and cutting frequency and regrowth.

Burton (1965a, 1966) and Burton *et al.* (1986) have demonstrated that later-maturing millet varieties produce leafier forage for a longer duration, have a better seasonal distribution of forage, are higher in protein content, and are easier to manage and more digestible than earlier varieties. Burton (1951) suggested that when about 45 cm tall, the crop could be grazed rotationally and mowing to prevent heading could extend the productive season and improve forage quality.

The stage of development at harvest greatly influences yield and regrowth habit. Beaty *et al.* (1965), Begg (1965), Fribourg (1966), and Clapp and Chamblee (1970) reported that as stubble height was raised regrowth from terminal buds increased while axillary and basal tillering remained constant. Stephenson and Posler (1984) observed that more tillers are initiated at the vegetative stage and at taller stubble heights. Basal tillering increased as the stubble height was lowered and regrowth at the boot stage was more dependent on reserve carbohydrates than at the vegetative stage. The root system has to be well developed to maintain new growth during the early phases of tillering (Clapp and Chamblee, 1970).

Total nonstructural carbohydrate has been shown to be used in part for regrowth following defoliation by Mays and Washko (1962). They reported substantial dependence on carbohydrate reserves when pearl millet was harvested to a 5-cm stubble height, and dependence decreased as the stubble height was raised to 15 cm. Plants cut at 15 or 20 cm had sufficient remaining photosynthetic tissue to supply the plant requirements for regrowth, whereas those cut at 5 or 10 cm utilized more reserve material.

Higher yields of palatable and digestible feed are obtained if pearl millet is harvested just as it comes to head. The yields reported in the literature vary widely, ranging from 18 to 45 t/ha, the latter when the season is favorable and the crop is allowed to reach maturity.

Hoveland and McCloud (1957) found that rows spaced 45.7 to 50.8 cm apart produced highest yields. Among several treatments investigated the best combination for production and quality was obtained when 76-cm plants were clipped to 45-cm stubble. Broyles and Fribourg (1959) suggested that pearl millet to be used for pasture or silage should be allowed to reach a height of 76 cm before it is grazed or cut down to 15.2 to 25.4 cm. Regrowth was more rapid from 15.2- to 20.3-cm stubble than from 7.6- to 10-cm stubble.

Beaty *et al.* (1965) reported that Gahi 1 pearl millet responded to a wider range of harvest conditions that Tift Sudan grass or Sudax 11, a hybrid between Sudan grass and sorghum. Harvesting at 5-week intervals increased forage production by 46% over harvesting every 2 weeks. Harvesting seven-eights of the plant increased production by 18% over harvesting one-third of available height. Mays *et al.* (1966) cut Sudan grass–sorghum hybrids, Sudan grass, and pearl millet to stubble heights of either 10 or 20 cm on reaching heights of 50, 86, and 120 cm. Yield averages for all crops indicated that those cut when 50 and 86 cm high, respectively, yielded 42 and 71% as much as those cut when 120 cm high. Cutting to a stubble height of 20 cm resulted in about 7% lower yields than cutting to a height of 10 cm.

Burger and Hittle (1967), using sorghum × Sudan grass hybrids, Sudan grass hybrids, pearl millet hybrids, and Sudan grass found that all produced superior yields at three harvests per year compared to four harvests. Better yields were obtained with a 7.6-cm stubble than with a 15.2-cm stubble. Hoveland *et al.* (1967) reported the protein content of sorghum–Sudan grass to be higher than that of pearl millet at several rates of nitrogen when harvested in the preboot stage with similar DM digestibility. They found a response to high rates of nitrogen from both species, but did not observe this to affect either DM digestibility or leaf percentage. In New South Wales, Australia, Ferraris and Norman (1973) suggested that for obtaining high, well-distributed yields coupled with quality, frequent harvests leaving a tall stubble of 30 cm was desirable. Although total productivity was favored by less intensive management, quality was improved by intensive cutting.

Management influences not only forage yields but also forage quality. Rusoff *et al.* (1961) found that lignin content progressively increased with plant maturity. Burton *et al.* (1964) reported that young leaf blades contained higher levels of CP, true protein, and lower levels of lignin than older leaves. Improvements in protein content were reported with frequent and severe cutting (Burger and Hittle, 1967) and with delay in sowing, and decreased stubble height was also reported (Hoveland and McCloud, 1957; Westphalen and Jacques, 1978). Decrease in protein content in forage with increasing age has also been reported (Hill, 1969; Patel *et al.*, 1958; Sehagal and Goswami, 1969).

Because forages are grown to feed animals, their digestibility, composition, and intake are of prime importance. Generally a good quality forage has a high leaf–stem ratio, is high in protein and digestible nutrients, and is low in fiber and lignin. Hart (1967) observed positive correlations between leafiness and DM digestibility. Lignin content was found to be a good predictor of digestibility. DM digestibility of leaves was significantly correlated with CP and crude fiber content, but less closely with lignin content. Achacoso *et al.* (1960) observed that as DM increased there were increases in both crude fiber and lignin content. They recorded highly significant and negative correlations for CP content with lignin, crude fiber, and DM.

D. GRAZING BY LIVESTOCK

Pastures provide the least expensive source of nutrients, as grazing of crops with cattle eliminates costs and losses of nutrients associated with harvesting, processing, storing, and feeding.

The palatability of pearl millet forage for dairy cows is high (Ball, 1903). Burton et al. (1964) reported that young leaves are much more palatable than older leaves. Norman and Phillips (1968) observed that cattle grazing on a mature and near-mature crop consumed first the earheads, followed by stems and leaves, and suggested that the order of preference was probably associated with digestible carbohydrate content.

Pearl millet pasture grazed rotationally by dairy cows provides total digestible nutrients (TDN) in the range 1400–2300 kg/ha, a quantity generally superior to that for Sudan grass and sorghum (Faires *et al.*, 1941; Roark *et al.*, 1952; Marshall *et al.*, 1953). Marshall *et al.* (1953) found that at an annual average of 2360 kg/ha of TDN, lactating cows derived 60% of their TDN intake while on millet pasture, which was adequate to support the requirement for body maintenance and 4.5 kg out of a daily production of 13.8 kg of 4% fat-corrected milk.

Miles *et al.* (1956) have shown that Tift sudan has consistently produced more DM, milk, and TDN than pearl millet but pearl millet consistently provided higher quality pasture than permanent pastures. Rollins *et al.* (1963) reported that intensively managed Gahi 1 pearl millet was the best forage for maintaining lactation, though a combination of pearl millet and Bermuda grass gave an equivalent production; both were superior to Bermuda grass alone. Experiments with lactating Jersey cows showed that pearl millet did not differ in the amount of grazing provided and was superior to Sudan grass in yield of dry forage (Baxter *et al.*, 1959). Average milk production was between 41.7 to 43.4 kg/day.

In South Africa, Penzhorn and Lesch (1965) observed that dairy cows found sweet Sudan grass more palatable than pearl millet. However, they grazed pearl millet readily and it gave a higher carrying capacity than sweet Sudan grass with similar average milk production.

McCartor and Rouquette (1977) studied livestock gains of weanling cattle and the factors affecting profitability of grazing pearl millet. The most important factor was the differential between the buying and selling price of the cattle, which the farmer seldom controls. Besides this factor, grazing pressure was an important determinant of profit. They concluded that greatest profit or least loss occurs at medium grazing pressures (approximately 2 kg of available forage per kilogram of animal live weight). They observed that pearl millet was difficult to manage as a grazing crop because of fluctuations in forage production over a relatively short period of time. Maximum live weight gains were achieved at low stocking rates, resulting in low forage utilization.

1. Weight gains of beef cattle on forage

Pearl millet proved to be the best temporary grazing pasture tested in Tifton, Georgia. Pearl millet grown on good soil, fertilized liberally, and grazed rotationally required only 0.12 ha to provide all the forage a dairy cow would consume. A succession of plantings of pearl millet is desirable for continuous grazing through the summer. Pearl millet planted in rows and cultivated once yielded 229 kg/ha of live weight gain and when grazed for about 80 days compared to 212 kg/ha for a broadcast crop (Georgia Coastal Plain Experiment Station, 1947).

Dunavin (1980) reported that total gains of 643 kg/ha when yearling cattle grazed on two successive plantings of pearl millet in the same season; animal gains produced by grazing the first plantings were significantly greater than those for the second planting. Norman and Stewart (1964) found that cattle grazing mature standing pearl millet in the dry season made an average live weight gain of 296 kg/ha in 16 weeks. Wet-season grazing by beef cattle in northern Australia gave gains of 102 kg/head in 20–24 weeks at 2.5 animals/ha (Norman, 1963).

In a 3-year study, Dunavin (1970) compared Gahi 1 pearl millet with two sorghum × Sudan grass hybrids as pasture for yearling beef cattle. Gahi 1 millet produced superior gains per hectare per day on both early (3.70 kg) and late (2.60 kg) planted pastures. Hoveland *et al.* (1967) reported only 0.45 to 0.57 kg/day on pearl millet and attributed these low gains to high moisture content in the forage. Johnson *et al.* (1978) evaluated the performance of dairy heifers grazing on Gahi 1, Gahi 3, and Tifleaf 1. Daily gain per animal averaged 0.63, 0.76 and 0.84 kg from Gahi 1, Gahi 3, and Tifleaf 1, respectively.

2. Effect of pearl millet grazing on milk fat

Grazing lactating cows on pearl millet is associated with depression in butter fat content of milk, a problem accentuated by high grain supplement levels (Clark *et al.*, 1965). Miller *et al.* (1963) found that the milk produced on millet pasture had only 2.85% butterfat compared with 3.64% from Sudan grass grazing. However, total production, nonfat solids, and protein content were similar. Hemken *et al.* (1968) indicated that fat depression was influenced by cation fertilization levels. Bucholtz *et al.* (1969) observed that cows grazing on pearl millet produced milk that is significantly lower in fat content and the fat contained a higher degree of unsaturation than when the cows were grazed on Sudan grass. The molar percentage of rumen butyrate was significantly reduced in cows grazed on pearl millet. The concentration of oxalic acid was significantly higher in pearl millet herbage than in Sudan grass. There was a trend toward higher concentrations of all minerals (Mn, K, Na) in pearl millet than in Sudan grass. Schneider and Clark (1970) suggested limiting K fertilization, correcting Ca and Mg deficiencies, and monitoring nitrate levels during periods of moisture stress to restrict nitrate toxicity. The same conditions also appeared to reduce oxalate and succinate levels with consequent increases in butterfat content.

A method to reduce oxalic acid content in pearl millet forage was suggested by Parveen *et al.* (1988). When pearl millet fodder cut at preflowering stage with 2.12% oxalic acid was soaked in water (1:10) for 30 min twice in succession, the oxalic acid content was reduced to 0.69%.

E. NITRATE TOXICITY

Poisoning is caused when cattle graze millet that is abnormally high in nitrates (Green, 1973). High amounts of nitrates are likely to occur in crops grown under stress situations such as drought, low temperatures, and diseases. Rouquette *et al.* (1980) reported that pearl millet grown under apparent drought stress conditions was unpalatable to grazing cattle and contained potentially toxic levels of nitrate and high levels of total alkaloids. In a study of 11 pearl millet lines by Krejsa *et al.* (1984), alkaloid levels ranged from 17 to 101 mg/kg and nitrate levels from 2.4 to 9.8 g/kg. Leaf blades contained more total alkaloids than stem plus sheaths, and stem plus sheaths contained more nitrate than leaf blades.

Stage of growth markedly changes the nitrate content of forages. Nitrate concentrations are higher in young plants and decrease as the plant matures. Leaves contain less nitrate than stems and harvest near maturity normally leads to lower levels of nitrate (Burger and Hittle, 1967). Nitrogen fertilizer also affects nitrate levels. Fribourg (1974) reported that nitrogen accumulation was highest in Sudan grass and pearl millet, especially in drought periods with high available soil nitrogen and potassium levels and with molybdenum deficiency. Oxalate was found to increase with increases in soil potassium level and drought stress. Lemon and McMurphy (1984) observed that nitrate levels increased with higher nitrogen fertilization, but decreased with later maturity stages. Lower portions of the plant contained 2.7 to 3.5 times more nitrate than the upper portions, suggesting that raising the cutting height would reduce the forage nitrate content.

Mefluidide, a quality-enhancing plant growth regulator in pearl millet, was shown to inhibit vegetative growth and increase nitrogen content and nitrate nitrogen. Concentrations of total nitrogen and nitrate nitrogen were inversely related to DM yield, suggesting that accumulations were a result of prolonged nitrate uptake in the absence of growth (Fales and Wilkinson, 1984). They advised caution in the use of mefluidide, as levels of accumulated nitrate nitrogen could be potentially hazardous to livestock.

F. SILAGE

Pearl millet produces good silage, as it is high in carbohydrates and DM content is sufficiently high to result in little or no excess moisture (Boyle and Johnson, 1968). The stage of maturity at harvest is an important factor influencing the composition and nutritive value of silage. Generally, addition of a carbohydrate preservative such as ground snapped corn or citrus pulp is required for making good silage.

Johnson and Southwell (1960) reported on the performance of animals fed on millet and maize silages. On DM basis the intake of millet silage by lactating Jersey cows was greater than that of corn silage. Though milk production from millet silage was significantly higher, differences in body weight gains were not significant. It appeared that cows fed millet silage obtained more net energy per unit DM intake than those fed corn silage. Similar results were reported by Lansbury (1959) and Sisk *et al.* (1960). Working with yearling steers, Baker (1970/1971) reported that pearl millet and sorghum × Sudan grass hybrid silage was more satisfactory than small-grain and perennial grass silage for yield and quality. However, summer annual grass silage often did not give as good results as comparable pasture.

Bertrand and Dunavin (1973) observed that steers grazing Gahi 1 millet pasture gained weight quicker than steers receiving Gahi 1 millet silage

(0.75 and 0.62 kg/head/day, respectively) and beef yield was slightly higher for steers receiving millet silage (495 versus 455 kg/ha). They concluded that the small increase in amount of beef produced would not compensate for the additional expenditures required for harvesting, storing, and feeding millet silage. Jaster *et al.* (1985) concluded that heifers consuming pearl millet and sorghum silages showed higher DM intake and DM digestibility than those consuming cool-season silages following evaluations under a forage double-cropping system.

Gupta *et al.* (1981) using cross-bred (Haryana × Jersey) cattle studied the improvements brought about in the nutritional quality of fodder when pearl millet and cowpea (*Vigna ungiculata*) were ensiled together. The digestibility coefficients for DM and CP content, IVDMD, digestible CP, and TDN were more for pearl millet–cowpea silage than for pearl millet alone. Similar results were reported by Freitas (1988).

For sheep, Silveira *et al.* (1981) reported that silage of pearl millet harvested at boot leaf stage in mixture with cowpea had a higher organic matter intake and digestibility than other silages. Crude protein increased from 7.2 in the fresh material to 8.6% in the silage. As the cell wall content was lower and digestibility higher, energy intake was higher and the sheep were able to retain consumed nitrogen. On the other hand, working with sheep, Singh and Mudgal (1980) observed that although cowpea and pearl millet can be successfully conserved as silage, protein and energy supplementation will be required for a practical feeding of animals. Andrade and Andrade (1982a) reported that a maximum dry matter yield of 21.9 t/ha was obtained at 134 days vegetative growth to produce acceptable silage. Sugarcane and molasses improved the quality of silage by reducing butyric acid and increasing lactic acid contents. However, in tests with sheep, CP, crude fiber, and DM digestibility were not significantly increased when sugarcane or molasses were added (Andrade and Andrade, 1982b).

VI. CONCLUSIONS

The potential benefits from the application of existing knowledge and from further research in pearl millet are substantial both for the food crop in low-resource agriculture and for the forage or feed grain crop in warm-temperate agriculture.

In low-resource agriculture the main benefits will come from research into grain processing and food product research as well as from plant breeding. Pearl millet foods must be as easy to make as those from rice and wheat, and the flour, or partially prepared grain, must have a longer shelf life. In India approximately 25% of the pearl millet crop is marketed, which is two to five times as much as in Africa (FAO, 1990). This has been a crucial factor in stimulating continued research and supporting a hybrid seed industry in India. In Africa, general economic factors and poor cereal markets have been major constraints to the adoption of yield-increasing technologies for dryland cereal production (OTA, 1988). Although the main constraints to production for pearl millet in Africa are recognized as low soil nutrient levels as well as low rainfall (Fussell *et al.*, 1987), the highest cost/benefit return comes from the adoption of new cultivars. The increase in pearl millet productivity of 2.3% per annum over the past 20 years in India following the adoption of new cultivars (Harinarayana, 1987) points to what can be achieved in Africa. However, producing cereal grain surplus to family needs for marketing must be equally or more attractive to the African farmer than alternative cash crop options. The increase in cultivar yield potential in either hybrids or varieties in India shows no indication of plateauing (Harinarayana, 1987; ICRISAT, 1991). Research in Africa has shown that both single-cross and topcross hybrids are substantially higher yielding than varieties (Kumar, 1987).

The steady development in the quality and yield of pearl millet as a forage crop in the United States over the last 50 years is a remarkable testimony both to the species and to plant breeding. The incorporation of the low lignin factor, currently under way in several breeding programs, will result in a significant improvement in forage digestibility. New sources of disease resistance, the identification of improved heterotic patterns, and the potential use of genes from related *Pennisetum* species may further improve productivity and use of pearl millet.

Possibly the greatest advances in the next decade will come from the development of pearl millet as feed grain crop, adapted to warm-temperate regions. In some respects, the development of pearl millet for the U.S. Midwest is following a course similar to that of soybeans 40 years ago where there was very little germplasm in which yield potential was not strongly associated with photoperiod sensitivity. Existing cultivars were then too late, tall, and weak-stemmed for use in the Midwest. Similarly, a market had not been developed. However, rapid progress has been made in reorganizing the pearl millet plant to a combine type and in building up yield levels in the dwarf early-maturing background. Though the good nutritional status of the grain is already established, opportunities for further genetic improvement in feed value are known to exist.

The benefits from basic research on pearl millet and related species and the application of biotechnology offer less certain but potentially far-reaching impacts. The possibility of transferring apomixis from *P. squamulatum* into pearl millet (Dujardin and Hanna, 1989) would essentially mean that hybrids could be cloned by seed increase. Gene mapping, both nuclear and cytoplasmic, by various methods is currently under way in several laboratories and will assist in locating important genes or quantitative trait loci, enhancing breeding efficiency. Anther culture and haploid development have been reported in pearl millet (Bui-Dang-Ha and Pernes, 1985; Bui-Dang-Ha *et al.*, 1986), as has protoplast formation and embryo regeneration (Vasil and Vasil, 1980; Lorz *et al.*, 1981), but there are no reports of further progress.

Increases in production and product quality are dependent in the long-term on the discoveries made from basic research. Research interest in pearl millet has been steadily growing as evidenced by the number and scope of recent publications, and Hanna (1987) comments that it is the "drosophila" of cereals for research. From discoveries already made and used in the crops' improvement, it is apparent that pearl millet has the potential to have a larger role in world agriculture, both as food and forage in the developing world and as feed and forage in temperate agriculture.

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