Charcoal Rot of Sorghum

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Summary

Charcoal rot of sorghum caused by the fungus Macrophomina phaseolina *is a root and stalk rot disease of great destructive potential in most sorghum-growing regions. Improved, high-yielding cultivars under good management tend to be very susceptible to the disease.* M. phaseolina *is a common soilborne, nonaggressive, and plurivorous pathogen that attacks plants whose vigor has been reduced by unfavorable growing conditions. Drought stress is the primary factor that predisposes sorghum to charcoal rot. In diseased roots and stalks,* M. phaseolina *is often associated with other fungi, suggesting that the disease is of complex etiology. Control by fungicides, cultural practices, and host resistance are briefly discussed, and priority areas for future research are listed.*

Charcoal rot, caused by *Macrophomina phaseolina* (Tassi) Goid., is the most common and probably also the most important root and stalk rot disease of sorghum. Reviews by Tarr (1962), Dhingra and Sinclair (1977, 1978), and Sinclair (these proceedings) provide comprehensive information on the biology of *M. phaseolina* and the epidemiology and control of the diseases it causes in many plant species. Several papers in these proceedings (Sessions III, IV, and V) discuss in detail the physiological and environmental factors that influence charcoal rot and its control by fungicides, cultural practices, and host resistance. In this review, emphasis will therefore be on those aspects of the pathogen and disease that have or may have important implications in disease control and management.

Occurrence and Geographical Distribution

Charcoal rot is a worldwide disease: it has been eported from all the ecologically diverse areas of sorghum culture in the tropics, subtropics, and temperate regions (Tarr 1962, ICRISAT 1980). When inoculum is present, the occurrence of charcoal rot in a particular area is greatly influenced, like most plant diseases, by environmental conditions. It may be widespread in some years and localized or even absent in others. In India the disease occurs on sorghums growing in both red (Alfisol) and black (Vertisol) soils. In general the worldwide distribution of the disease would indicate its occurrence on many different soil types.

Symptoms

A variety of symptoms are associated with charcoal rot. These include root rot, soft stalks, lodging of plants, premature drying of stalks, and poorly developed panicles with small inferior-quality grain (Hsi 1956, Uppal et al. 1936).

The most striking and usually first indication of the disease is lodging of plants as they approach maturity. Lodging is due to the weakened condition of the stalk, caused by the disintegration of the pith and cortex by the pathogen, leaving the lignified fibrovascular bundles suspended as separate

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International Crops Research Institute for the Semi-Arid Tropics. 1984. Sorghum Root and Stalk Rots, a Critical Review: Proceedings of the Consultative Group Discussion on Research Needs and Strategies for Control of Sorghum Root and Stalk Rot Diseases, 27 Nov - 2 Dec 1983, Bellagio, Italy, Patancheru, A.P. 502 324, India: ICRISAT.

strands in the hollow stalk; hence "hollow stalk of sorghum" as the disease was first named by Uppal et al. (1936). The vascular bundles are profusely covered with tiny black sclerotia of the pathogen, which give the charcoal appearance to the affected area. Thus the name "charcoal rot" describes the appearance of the disease inside infected roots and stalks.

Sometimes charcoal rot symptoms are not easily noticeable. Harris (1962) reported that in Nigeria the disease escaped attention because symptoms were inconspicuous. Affected plants looked healthy but had much thinner stalks than normal and had very small panicles.

M. phaseolina may also infect seedlings, causing seedling blight or damping-off symptoms under moist and high temperature conditions (Uppal et al. 1936). There is also one report of the pathogen causing leafspot symptoms in sorghum (Raut and Bhombe 1972). Very little is known about these two phases of the disease.

Economic Importance

In order to determine the research needs and strategies for control of charcoal rot, a realistic definition of the problem with reference to crop losses is required. The literature contains many reports on the destruction of sorghum crops by charcoal rot, but sound and reliable quantitative data on yield losses are not given. Uppal et al. (1936) determined that the disease was of "sufficient economic importance" on postrainy-season crops in Maharashtra State, India. Harris (1962) reported that in Kano, Nigeria, charcoal rot caused "considerable loss in yield." In nearby Cameroon S.B. King and D. Barry (Major Cereals in African Project, Samaru, Nigeria, 1970; unpublished report of a trip to Cameroon and Chad) saw severe symptoms of charcoal rot in farmers' fields and estimated yield losses of over 50%. Similarly "serious losses" in several states in the USA were reported, but no quantitative data on crop loss were given (Leukel et al. 1951).

In spite of the lack of data on field crop losses, the destructive potential of charcoal rot in susceptible cultivars is unquestionable. Four types of crop losses may be recognized: (1) loss in grain yield and quality due to stunted plants, smaller stalks than normal, and premature drying; (2) poor crop stands due to seedling blight; (3) complete loss of yield in lodged plants where mechanical harvesting of grain is practiced, and where harvesting is manual, destruction of lodged plants by termites [illegible] other animal pests before the grain or fodder [illegible] collected; (4) loss in quality and quantity of fodder due to infection and destruction of the stalk.

Under experimental conditions we have obtained 100% lodging and grain yield losses of 23 to 64% in CSH-6 hybrid at three locations in India and one in Sudan (Table 1). In these experiments natural charcoal rot infection of plants was induced by subjecting them to drought by withdrawing irrigation at different growth stages; grain yield was determined from both lodged and standing plants. Although drought alone must have contributed to some yield reduction, the combined effects of drought and charcoal rot that caused plants to lodge must have greatly increased the level of yield

Table 1. Lodging and yield of charcoal-rot-infected CSH-6 sorghum under four moisture stress treatments at four locations in 1981.

Moisture stress treatments	Locations, lodging (%), and plot yield (kg/18 m²)							
	ICRISAT Center (India)		Dharwar (India)		Nandyal (India)		Wad Medani (Sudan)	
	Lodging (%)	Yield	Lodging (%)	Yield	Lodging (%)	Yield	Lodging (%)	Yield
Irrigation to grain maturity	8	2.2	7	3.3	1	3.0	3	2.1
Irrigation to 50% anthesis	42	2.2	86	2.5	2	2.0	5	1.9
Irrigation to boots swollen	46	1.8	100	2.1	36	1.7	56	1.9
Irrigation to ligule visible	55	1.6	100	1.7	47	1.1	73	1.6
SE ±	3.54	0.08	1.92	0.10	3.51	0.17	3.13	0.10
Loss in yield (%) [a]	27		48		64		23	

a. $\frac{\text{Irrigation to grain maturity - irrigation to ligule visible}}{\text{Irrigation to grain maturity}} \times 100$

loss. At Dharwar a 35% reduction in 1000-grain weight was recorded when this technique was used. Similarly Anahosur and Patil (1983) reported 15-55% loss in grain weight in their experiments conducted at Dharwar. These data on grain yield losses clearly show the economic importance of the disease when it occurs as plants approach maturity. However, there is still need for more data, particularly on the various types of losses described above from surveys in farmers' fields.

Improved, high-yielding cultivars tend to be ultra-susceptible to charcoal rot. Improved varieties and hybrids that revolutionized sorghum production in India in the 1970s (Rao 1982) have proved very susceptible to the disease, with 100% lodging in severe cases (Nagarajan et al. 1970, Anahosur and Rao 1977, Avadhani and Ramesh 1979). In West Africa high-yielding exotic cultivars tend to be very susceptible to charcoal rot (J.F. Scheuring, ICRISAT/Mali Program, personal communication, Feb 1983). The susceptibility of improved cultivars to charcoal rot poses a serious problem for sorghum improvement programs worldwide, and a solution must be found that would enable farmers to benefit from the use of improved cultivars.

Causal Organism

The causal organism of charcoal is a common soilborne fungus often known by its imperfect state *Macrophomina phaseolina* (Tassi) Goid. (Domsch et al. 1980). The perfect state is called *Sclerotium bataticola* Taub. Eight synonyms that may be encountered in the literature are: *Macrophomina phaseoli* (Maubl.) Ashby, *Macrophomina philippines* Petr., *Macrophomina crochori* Sawada, *Macrophomina cajani* Syd. & Butl., *Macrophomina sesami* Sawada, *Rhizoctonia bataticola* (Taub.) Butl., *Rhizoctonia lamellifera* Small, and *Dothiorella cajani* Syd. & Butl. (Holliday and Punithalingam 1970).

Association with Other Fungi

In diseased roots and stalks with conspicuous signs of charcoal rot, fungal isolations usually reveal the association of *M. phaseolina* with other fungi. In Texas, USA, both *M. phaseolina* and *Fusarium moniliforme* were obtained in cultures of diseased stalks (Tullis 1951). Similar observations were made in Georgia, USA (Luttrell 1950), and in India (ICRISAT 1983). In Argentina, where *F. moniliforme* was the predominant fungus isolated from lodged plants, 40% of the isolations were *M. phaseolina*. Other fungi isolated included unidentified *Fusarium* spp, *Rhizoctonia solani*, *Helminthosporium sativum*, and *Nigrospora sphaerica* (Frezzi and Teyssandier 1980). Similarly, in New South Wales, Australia, systematic surveys to assess the relative importance of fungi associated with root and stalk rots revealed that, although *F. moniliforme* was predominant, *M. phaseolina* and *N. sphaerica* were regularly isolated simultaneously from diseased roots and stalks (Trimboli and Burgess 1982).

Data cited above show clearly that in most cases of charcoal rot, *M. phaseolina* is not the sole cause of the disease under natural field conditions, but acts in combination with other pathogens to produce it. In other words, what is visually identified as charcoal rot is a sign of one fungus among several in a disease of complex etiology. Wadsworth and Sieglinger (1950) suggested that the several fungi associated with stalk rots attack in some orderly sequence, with *M. phaseolina* being the last and most conspicuous of the sequence. Leukel et al. (1951) also suggested that root and stalk invasion by *M. phaseolina* is preceded by *F. moniliforme*. P. Mayers (Department of Primary Industries, Queensland, Australia; personal communication, Aug 1983) has suggested that temperature influences the dominance of a particular pathogen in the disease complex. *F. moniliforme* is the dominant fungus under low soil temperatures, whereas *M. phaseolina* predominates at high soil temperatures. The pathological significance of the involvement of several fungi in causing root and stalk rot is not known and must be investigated.

Host Range and Physiological Specialization

M. phaseolina is a plurivorous pathogen of over 75 different plant families and about 400 plant species (Dhingra and Sinclair 1977). Among these are important food crops, such as cereals (maize, sorghum, and finger millet), legumes (cowpea, groundnut, soybean, pigeonpea, and chickpea), vegetables (cabbage, tomato, and pumpkin), and fruits (apple, pear, orange, and banana). As its wide host range suggests, *M. phaseolina* is a highly variable pathogen in both its pathogenicity and mycological characteristics. Some isolates of the pathogen are host specific (Hildebrand et al. 1945), while others can attack a wide range of hosts (Holiday and Punithalingam 1970). Physiological races has been reported for isolates of some crops such as jute (Ahmed and Ahmed 1969), and variability in cultural characteristics and pathogenicity of isolates from different parts of the same plant has been reported in soybean (Dhingra and Sinclair 1973).

Pathogen variation and physiological specialization are important factors that require consideration in disease control programs using host resistance. In the case of charcoal rot of sorghum, it would be useful to know (a) if sorghum is susceptible to isolates of the pathogen from other plant species and (b) whether physiological races exist among sorghum isolates of the pathogen. Unfortunately such information is not available in the literature.

Biology and Epidemiology

Most of our knowledge of the biology of *M. phaseolina* is derived from results of research with isolates from crops other than sorghum. It is assumed that the general biology of sorghum isolates is similar to that of isolates from other crops, although the pathosystem may be different. As stated in our introduction, only those aspects of the biology that influence the pathosystem will be reviewed.

Source and Survival of Inoculum

M. phaseolina is a root-inhabiting fungus (Garrett 1956), with little or no saprophytic growth in either soil or dead host cells of infected plants (Norton 1953, Edmunds 1964). In the absence of host plants, it survives or overseasons predominantly as small black sclerotia in diseased root and stem debris or in soil after decay of the plant material in which they were formed (Smith 1969a, Bhattacharya and Samaddar 1976). Thus the primary source of inoculum is sclerotia in the soil. Cook et al. (1973) reported that after 16 months in soil, 23% of sclerotia from sorghum stalks germinated. Sclerotia from other plant hosts are known to survive for several years (Dhingra and Sinclair 1977).

Populations of sclerotia in a maize field ranged from zero to more than 1000/g of soil (Papavizas and Klag 1975). This great variation in inoculum density in soil is one of the factors responsible for the highly variable incidence of charcoal rot in the field. According to Meyer et al. (1973), inoculum density increased in soil with continuous cropping of a susceptible crop of soybeans. This has implications in disease management strategies, which will be discussed later.

Root Penetration and the Effects of Drought Stress on Host Colonization and Disease Development

The process and mechanisms by which *M. phaseolina* penetrates roots and colonizes sorghum roots and stalks are not clearly known or understood. It is assumed from the work of Smith (1969b) with pine and Bhattacharya and Samaddar (1976) with jute that sorghum root exudates stimulate the germination of sclerotia in the soil. What happens next is still being debated. Reports in the literature can be summarized into two views. The first view is that mycelia from germinating sclerotia penetrate rootlets at any time, but no further growth or colonization takes place until the plants are drought stressed, when the pathogen grows extensively and colonizes roots and stalks (Norton 1958). In the second view, exemplified by the work of Odvody and Dunkle (1979), root penetration does not occur until plants are drought stressed. Whatever the truth is with regard to time of penetration, it is clear from the literature that colonization of root and stalk tissue and charcoal rot development occur only when plants are drought stressed during the grain-filling stage (Edmunds 1964, Edmunds and Voigt 1966, Odvody and Dunkle 1979).

Drought causes harmful physiological or metabolic changes in the plant. It reduces plant vigor; plants so affected are predisposed to attack by nonaggressive pathogens such as *M. phaseolina* (Schoeneweiss 1978). From a review of stalk rot problems in maize and sorghum and the associated environmental factors, Dodd (1977, 1980) developed a "photosynthetic stress-translocation balance" concept to explain the predisposition of sorghum to charcoal rot. According to this hypothesis:

a. sorghum plants are predisposed to charcoal rot as the root cells senesce because of a reduction of carbohydrates to maintain metabolic functions, including resistance;

b. the availability of carbohydrate to the root tissue is influenced by the environmental stresses affecting photosynthesis and by competition for carbohydrate by the developing grain;

c. if the combination of photosynthetic stress and translocation balance reduces carbohydrate to root tissue, root cells and also those of the lower part of the stalk senesce and lose resistance to the charcoal rot pathogen;

d. the charcoal rot pathogen invades and destroys root tissue, and subsequently rots the stalk, reducing its strength. This frequently results in lodging.

Although many environmental factors reduce photosynthesis, and hence assimilate (photosynthate) supply, drought stress at grain filling is the primary factor that triggers events that eventually lead to charcoal rot disease and plant lodging.

Dodd's hypothesis implies that the interaction of drought stress and pathogens causes stalk rots and lodging. Direct evidence for this has been provided by P. Mayers (Department of Primary Industries, Queensland, Australia; personal communication, Aug 1983), who reported as follows:

> In field experiments Fusarium stalk rot (*F. moniliforme*) and subsequent lodging developed when plant moisture stress and high inoculum density interacted. Minimal and severe moisture stress were obtained by using irrigation and rain excluding shelters. In the presence of inoculum, stress accentuated stalk rot 13.5 fold. Natural and very low levels of Fusarium inoculum were achieved by soil fumigation with dazomet. Fumigation decreased stalk rot from 59.3% to 1.3% in the most susceptible hybrid. Mean stalk rot percentage was below 2.8% in non-stressed plots irrespective of inoculum level and was below 1.7% on fumigated plots irrespective of stress level. Extensive stalk rot developed only in non-fumigated, moisture stressed plots.

Henzell and Gillieron (1973) and Chamberlin (1978), on the other hand, hold the view that plant lodging under drought stress is a purely physiological problem. Drought stress reduces assimilate supply to the lower part of the stalk for maintenance respiration. This results in senescence, disintegration of pith cells, and hence lodging. These two views on the causes of lodging are fully discussed by Henzell et al. (these proceedings). It is acknowledged that drought stress alone can cause lodging without assistance from pathogens where inoculum is absent. However, where pathogens are present, drought-stressed plants are invariably invaded by them, and this leads to increased damage of plants. It is possible that low or intermediate levels of drought stress may be tolerated by the plant except when combined with the pathogen. There is an obvious need for further research to clarify these issues.

Cultural Practices and Charcoal Rot

Nitrogen fertilization and plant densities have been reported to influence charcoal rot. In India the high levels of nitrogen fertilization needed to maximize the yield potential of improved cultivars increase the severity of charcoal rot (Avadhani et al. 1979, Mote and Ramshe 1980). Patil et al. (1982) reported cultivar differences in the effect of plant density on charcoal rot. While charcoal rot incidence was significantly higher in the hybrid CSH-8R at 180000 plants/ha than at 45000 plants/ha, no differences were detected in the varieties SPV 86, SPV 265, and M 35-1. In a factorial experiment using line-source irrigation, we obtained highly significant positive correlations between drought stress, plant density, and nitrogen level (Table 2). It appears that high plant density increases plant competition for available soil moisture and that this competition increases with drought. The effect of nitrogen in increasing charcoal rot is probably due to its indirect effect on the ratio of root-to-shoot growth. Nitrogen promotes luxuriant shoot growth, and root development suffers. Under drought stress, the lack of a sufficient root system reduces the ability of a plant to obtain moisture, while at the same time its water requirement is increased by the luxuriant growth (Ayers 1978).

Systems of crop management that reduce pathogen inoculum and increase conservation of soil water decrease the incidence of charcoal rot. Sorghum grown under minimum tillage (ecofallow) in a winter wheat-sorghum-fallow rotation had 11% stalk rot, compared to 39% in conventional tillage (Doupnik and Boosalis 1975).

Sorghum grown in a mixed crop situation has also been reported to suffer less charcoal rot damage than sole crop sorghum (Khume et al. 1980).

Table 2. Percent lodging in CSH-6 sorghum at three levels of nitrogen and three plant populations subjected to ten different moisture stress levels with line source irrigation at ICRISAT Center.

Plant density and moisture stress	Percent lodging			
	Nitrogen levels[a]			
	N_1	N_2	N_3	Mean
D_1[b]	7.57	3.83	6.38	5.93
Stress-1[c]	0.00	1.98	5.24	2.41
Stress-2	1.08	1.09	3.26	1.81
Stress-3	0.36	0.84	2.44	1.21
Stress-4	1.57	1.39	2.09	1.68
Stress-5	0.69	0.64	0.76	0.70
Stress-6	0.00	0.69	0.00	0.23
Stress-7	9.83	7.09	8.76	8.56
Stress-8	21.52	11.64	14.18	15.78
Stress-9	14.35	6.97	11.03	35.35
Stress-10	26.30	5.94	16.00	16.08
D_2	13.91	18.40	18.76	17.02
Stress-1	1.01	5.88	3.00	3.30
Stress-2	0.55	1.42	7.58	3.1[illegible]
Stress-3	2.93	3.03	9.85	5.2[illegible]
Stress-4	2.25	6.73	3.24	4.07
Stress-5	4.43	12.69	7.97	8.36
Stress-6	7.63	11.24	6.78	8.55
Stress-7	13.33	23.59	18.21	18.38
Stress-8	30.13	37.78	30.64	32.85
Stress-9	37.77	36.43	45.73	39.98
Stress-10	39.03	45.19	54.76	46.33
D_3	29.40	37.00	36.17	34.19
Stress-1	1.95	4.54	7.34	4.61
Stress-2	4.83	6.12	10.73	7.23
Stress-3	4.43	8.26	10.35	7.68
Stress-4	9.35	9.48	13.12	10.65
Stress-5	17.68	31.72	28.83	26.08
Stress-6	24.37	49.76	38.12	37.42
Stress-7	43.34	63.07	49.34	51.92
Stress-8	51.62	58.45	55.16	55.08
Stress-9	65.14	69.97	71.77	68.96
Stress-10	71.30	68.62	76.92	72.28
Mean	16.96	19.74	20.44	19.05
SE (±) Density	2.73	2.35	3.09	1.58
SE (±) Stress	3.05	2.46	3.17	1.68
SE (±) Stress × density	5.29	4.26	5.49	2.91

a. N_1 = 20 kg nitrogen/ha
N_2 = 60 kg nitrogen/ha
N_3 = 120 kg nitrogen/ha

b. D_1 = 66675 plants/ha
D_2 = 133350 plants/ha
D_3 = 266700 plants/ha

c. Stress-1 = Nearest to line source (minimum moisture stress level).
Stress-10 = Farthest from line source (maximum moisture stress level).

Control

Several approaches have been investigated for charcoal rot control. As these will be fully covered in papers by various authors in these proceedings, only brief discussions of their effectiveness and application will be made in this section.

Fungicides

There are very few reports on the control of charcoal rot of sorghum by fungicides. Rajkule et al. (1979) reported that soil treatment with thiram at sowing did not effectively control the disease, but reduced it by 15%. Brassicol treatment had a similar effect. However, Anahosur et al. (1983) obtained no reduction in disease with Brassicol in field trials.

Soil fumigation treatments are generally successful in controlling *M. phaseolina* attack in other crops, e.g., in forest pine nurseries (Watanabe et al. 1970) and in melons (Krikun et al. 1982). Whether similar treatments would be effective in sorghum fields needs to be investigated. In practical terms, however, the cost and technological knowledge required for their successful use would preclude their adoption in areas where sorghum is a low-cash-value crop grown mostly by small farmers.

Williams and Nickel (these proceedings) provide more information about the prospects for fungicidal control of charcoal rot of sorghum.

Host Resistance

The four essential requirements for the identification and utilization of host resistance to charcoal rot have been discussed by Mughogho (1982). Our concern here will be to review briefly the techniques used to identify resistance, resistance sources, and factors associated with resistance. Comprehensive reviews of breeding for host resistance are available in papers by D.T. Rosenow, A.B. Maunder, and Henzell et al. (these proceedings).

Resistance Screening Technique

A reliable, efficient, and epidemiologically sound resistance screening technique for charcoal rot is yet to be developed. Following are three essential requirements of such a technique: (a) adequate inoculum density of *M. phaseolina* must be uniformly present in a virulent condition in the soil (since entry into plants is through roots) in which test genotypes are to be grown, (b) test genotypes should be subjected to the optimum and graded levels of drought stress at the appropriate growth stage to make them sufficiently predisposed to infection, and (c) a disease scoring scale that takes into account both root and stalk rot should be used.

Methods currently used to screen for resistance to charcoal rot do not adequately meet these conditions. The procedure followed by most investigators is essentially that reported by Edmunds et al. (1964). Sorghum is grown under irrigation in an environment known to be favorable for charcoal rot. Drought stress is induced by withholding irrigation at selected stages of plant maturity, and stalks are inoculated by inserting mycelium- and sclerotia-bearing toothpicks into holes made just above the first node. Amount of lodging, soft stalks, and the spread of the fungus from the point of inoculation up the stem are the three measurements taken in assessing the reaction of genotypes to the disease.

Toothpick inoculation and other methods where inoculum is introduced into the plant through the stalk are unsatisfactory primarily because they do not closely simulate the natural infection process, which begins in the roots and only later goes up the stem. Furthermore, the level of disease development with toothpick inoculation is usually less than that which occurs naturally and is therefore unsatisfactory for assessing resistance that could be useful under natural disease incidence (Edmunds et al. 1964).

At ICRISAT we have successfully induced charcoal rot without artificial inoculation in field-grown, susceptible sorghums by two methods. One method is to sow the crop just before the end of the rainy season so that it grows and matures under progressively less soil moisture. This timing is similar to that of the postrainy-season (rabi) crop in India, which suffers most from charcoal rot. The other method is to grow the crop under irrigation during the dry season and to withdraw irrigation at 50% flowering. In both methods charcoal rot incidence and severity vary according to location, probably due to soil type, level of moisture stress, and the pathogen inoculum potential in the soil (see Tables 1 and 2). Nevertheless, disease development in susceptible genotypes is sufficiently high for useful evaluation of test genotypes.

Anatomical and Physiological Factors Associated with Resistance

Several anatomical and physiological plant characters have been associated with resistance to charcoal rot and suggested as selection criteria in resistance screening programs. Maranville and Clegg (these proceedings) discuss the correlation of "stalk strength" with resistance to charcoal rot. Although much variation exists in the stalk anatomy of genetically diverse sorghum lines (Schertz and Rosenow 1977), there is no experimental evidence yet of this variation being associated with resistance.

Maunder et al. (1971) reported that in a charcoal rot nursery where plants were drought stressed from the boot stage to maturity, "bloomless plants" had 38.4% more disease than those with the waxy bloom on the stalk internodes. They suggested that bloomless plants were more predisposed to charcoal rot than "bloomed plants." Further research is needed to confirm this.

The most promising plant character that is positively correlated with charcoal rot resistance, and is increasingly used as a selection criterion, is nonsenescence. Rosenow (1980) reported significant correlations between nonsenescence, lodging resistance, and charcoal rot resistance in Texas, USA. Selection for charcoal rot resistance is based on the degree of nonsenescence exhibited by plants under drought stress during the late grain development stage. Both Duncan and Rosenow (these proceedings) provide more detailed descriptions of the nonsenescence character and its utilization in selection and breeding for charcoal rot resistance.

In India we also found significant positive correlations between charcoal rot resistance and plant nonsenescence (Table 3). However, multilocational testing for stability of the nonsenescence character showed that lines nonsenescent at one location were not necessarily nonsenescent at another location (Table 4), indicating the location specificity of the character. This would be expected from variations in pathogen inoculum density and in the level of drought stress to which plants are subjected during evaluation at different locations. Stability of nonsenescence would most probably depend on the level of drought stress. Up to a specific level of stress, a genotype would show stability in nonsenescence at several locations, but beyond that it may not. Further research is obviously needed to elucidate this.

Disease Rating Scale

Several disease rating scales have been used to evaluate sorghum lines for resistance to charcoal rot or stalk rots in general. The most commonly used is a 1-to-5 scale based on the percentage lodged plants, where 1 = no lodged plants and 5 = over 20% plants lodged (Frezzi and Teyssandier 1980). The main disadvantage of this method of disease evaluation is that it excludes infected plants that have not lodged. It is not uncommon in a charcoal rot nursery to see standing plants that are infected by the disease. Where toothpick inoculation is carried out, a rating scale based on the growth of the pathogen up the stem from the point of inoculation is used (Rosenow 1980). As discussed earlier under "Resistance screening technique," this method of inoculation and evaluation is epidemiologically unsound since infection is through the root system in nature. In the ICRISAT charcoal rot research project we have developed a rating scale that takes into account root infection, soft stalk of infected plants that do not lodge, and lodged plants. This scale is laborious to use when

Table 3. Correlation coefficients among parameters of charcoal rot disease scores under depleting soil moisture condition at four locations in India (Patancheru, Dharwar, Nandyal, and Madhira).

Disease parameter	Lodging (%)	Soft stalk (%)	Mean no. of nodes crossed	Mean score[a] for root infection	Leaf and plant death[a]
Lodging (%)		0.96**	0.88**	0.57**	0.65**
Soft stalk (%)			0.88**	0.52**	0.60**
Mean no. of nodes crossed				0.47**	0.52**
Mean score for root infection					0.92**
Leaf and plant death					

Correlation coefficient at 5% = 0.288, at 1% = 0.372 (**significant at 1%).

a. Based on three locations (Patancheru, Dharwar and Nandyal).

Table 4. Days to flowering, plant height (m), leaf and plant death, grain weight, percent lodging, percent soft stalk, mean number of nodes crossed, and mean score for root infection of six sorghum genotypes (rated as nonsenescent) at four locations in India during 1981 postrainy season.

Genotype	Location	Days to 50% flowering	Plant height (m)	Leaf[a] and plant death	1000-grain weight (g)	Percent lodging	Percent soft stalk	Mean no. of nodes crossed	Mean[b] score of root infection
IS-108	Patancheru	56	0.85	2.50	29.87	0.00	0.00	0.50	3.00
	Dharwar	47	1.62	4.42	19.94	44.62	37.50	1.17	4.00
	Nandyal	53	1.60	4.50	27.68	40.00	55.00	2.00	4.50
	Madhira	55	1.75	2.27	23.82	10.22	3.55	0.31	2.25
IS-176	Patancheru	70	1.25	4.00	26.48	25.00	40.00	0.70	4.50
	Dharwar	59	1.75	4.55	17.10	43.17	62.50	1.67	4.50
	Nandyal	71	1.19	2.40	34.17	5.00	5.00	0.05	3.00
	Madhira	65	1.35	3.36	25.53	0.00	0.00	0.43	1.50
IS-2954	Patancheru	67	1.10	4.50	25.90	20.00	50.00	1.10	5.00
	Dharwar	60	1.35	3.60	24.81	2.38	5.00	0.15	2.00
	Nandyal	71	1.00	2.60	30.66	0.00	15.00	0.80	1.95
	Madhira	65	1.25	4.00	27.67	30.00	61.85	1.53	4.00
IS-3927	Patancheru	61	0.75	4.30	50.97	55.00	55.00	1.95	5.00
	Dharwar	57	1.12	2.95	34.44	26.25	15.00	0.35	2.00
	Nandyal	60	1.05	3.55	40.66	45.00	50.00	2.80	4.00
	Madhira	59	1.25	2.80	45.74	0.00	13.35	0.33	2.50
IS-10722	Patancheru	65	1.15	3.60	31.88	25.00	25.00	0.55	4.50
	Dharwar	60	1.20	3.22	24.32	22.80	35.00	0.75	2.50
	Nandyal	71	0.95	2.90	46.36	10.00	20.00	0.85	3.25
	Madhira	66	1.40	4.07	19.82	48.75	48.75	2.00	4.00
CSH-6	Patancheru	62	1.15	4.79	26.95	78.75	85.00	2.65	4.73
	Dharwar	62	1.57	4.70	25.62	57.41	72.18	2.32	4.87
	Nandyal	67	1.25	4.08	25.22	100.00	100.00	4.70	5.00
	Madhira	56	1.34	4.91	26.36	83.67	92.36	5.41	4.93
SE for cultivar (±)		2.16	2.05	0.26	2.12	9.21	8.91	0.69	0.46
SE for location (±)		0.46	0.44	0.056	0.45	1.97	1.91	0.15	0.14

a. Nonsenescence ratings based on leaf and plant death scores on 1-5 scale, where 1 = completely green and 5 = dead.

b. Root infection score on 0-5 scale, where 0 = no discoloration and infection; and 5 = more than 50% roots showing infection and discoloration.

large numbers of material are to be evaluated. Nevertheless it is essential that the different phases of the disease are considered in a resistance screening program. Since leaf and plant death (senescence) are positively correlated with charcoal rot infection, a leaf and plant death scoring scale would be most useful for disease evaluation of large numbers of plants.

Resistance Sources

Attempts to find sources of resistance to charcoal rot for breeding programs were started in the USA in the 1940s. In one of the most comprehensive testing programs Hoffmaster and Tullis (1944) screened 232 sorghum lines of diverse genetic background at 4 locations for 4 years. Although they found differences in the susceptibility of these lines to charcoal rot, data showed no stability in the performance of the lines from year to year. They thus concluded, "it is impossible from the data available to recommend certain varieties for localities in which *Macrophomina* dry rot is a limiting factor."

In the ICRISAT charcoal rot research project we have also found inconsistencies in the reaction to the disease of a large number of germplasm lines.

This lack of stability is due, as explained earlier, to different levels of drought stress and hence different levels of predisposition to the disease. However, one line, E 36-1, has consistently shown resistance to lodging at several locations in 3 years of testing. The plants were infected, as shown by fungal isolations from roots and stalks, but the infection was not severe enough to cause lodging (ICRISAT 1982).

In the USA the line New Mexico-31 released by Malm and Hsi (1964) as resistant to charcoal rot has been used extensively in breeding programs. In recent years Rosenow (1980) identified 13 nonsenescent lines as good sources of resistance to charcoal rot. The stability of resistance of these lines outside Texas is not known. They should be tested for use in other countries where charcoal rot is a problem.

The need for stable and better sources of resistance is obvious. Most of the large (over 20000 lines) ICRISAT sorghum germplasm collection has not been screened, and it is conceivable that among these (especially among lines from drought-prone areas) are lines resistant to charcoal rot. However, the priority should be to develop a reliable screening technique that can be used to distinguish resistant from susceptible lines under graded levels of drought stress.

Crop Management

The ideal and most effective control strategy for charcoal rot is to prevent drought stress from predisposing plants to infection. In other words, resistance to predisposition would be the best method of control. This can be done by proper management of the soil-plant-water system. Except where sorghum is grown under irrigation, farmers have no control over the variability of rainfall in most sorghum-growing areas. Cultural practices that reduce pathogen inoculum in soil and that increase water availability and use by plants (e.g., plant density, rate of nitrogen fertilization, use of varieties with different rooting characteristics, and crop rotation) have been suggested as possible measures of reducing drought-stress-related diseases (Cook and Papendick 1972). Such measures have been successful in controlling fusarium foot rot of wheat (Cook 1980). Whether similar crop husbandry practices would be effective and practicable for control of charcoal rot awaits investigation.

Drought resistance as an indirect method of charcoal rot control raises the obvious and important question: will genotypes that resist drought also resist charcoal rot? We are unable to answer this question because we have insufficient knowledge of the interactions of drought stress, the charcoal rot pathogen, and the host. The only proposition we can offer is that certain levels of drought stress may be resisted by plants in the absence of the pathogen. Where the pathogen is present, such plants may be infected; the pathogen then destroys roots, which contributes to further drought stress. Therefore breeding for drought resistance alone may not provide the answer to the charcoal rot problem.

Priorities for Future Research

This review will have shown that in spite of its importance, research on charcoal rot has been largely superficial. Wide gaps still exist in the biology of the pathogen and epidemiology of the disease, and in particular, the process of pathogenesis and how it is influenced by environmental and plant physiological factors. The technical problems of working with a soilborne, root-infecting pathogen are partly responsible for these deficiencies. However, techniques are now available that could profitably be used in charcoal rot research.

Following are some of the areas that need research attention in the future:

1. **Crop loss.** Quantitative crop loss data are needed that distinguish between direct effects of drought and indirect effects through crop predisposition and subsequent damage by charcoal rot. Under what conditions are indirect effects more important than direct effects?
2. **Pathogenesis.** Root rot precedes stalk rot. When, in the growth stage of the plant, and under what conditions are roots penetrated by the pathogen? What conditions favor root and stalk colonization?
3. **Interactions with other pathogens.** Since *M. phaseolina* does not infect plants alone, there is need for basic studies on the interactions among the different pathogens involved. What is the sequence of infection? Is there synergism in host-parasite interaction?

4. **Pathogen variation and physiological specialization.** In view of the wide host range of *M. phaseolina*, it would be useful for control of the disease to know (a) if sorghum is susceptible to pathogen isolates from other hosts, and (b) whether physiological races exist among the sorghum isolates.
5. **Predisposition by drought stress and plant growth stage.** What level of drought stress (plant water potential) is optimum for predisposing plants to infection? Is there a varietal difference in this? Can charcoal rot occur in plants at all growth stages if sufficiently predisposed?
6. **Predisposition and plant water potential.** In screening for resistance, can we actually relate predisposition of plants to actual measurements of plant water potential? Graded levels of soil moisture supply, and hence predisposition, can be provided by the line-source irrigation technique.
7. **Sink.** Improved high-yielding varieties and hybrids tend to be ultrasusceptible to charcoal rot. Is it sink size or other factors that make such cultivars vulnerable to the disease? Can we identify the conditions under which a given size of sink is likely to indirectly predispose plants to infection?
8. **Association of nonsenescence and disease resistance.** Study the physiological basis of nonsenescence, its stability under different environmental conditions, and its relationship to charcoal rot resistance.
9. **Correlation between drought resistance and charcoal rot resistance.** Since drought stress is the primary factor that predisposes plants to charcoal rot, would drought-resistant plants also resist charcoal rot?
10. **Development of a reliable field screening technique.** This is essential for success in breeding for resistance.

Answers to most of the questions raised above would require interdisciplinary and collaborative research efforts between pathologists, physiologists, breeders, and soil scientists. We hope that the proceedings of this meeting will help to bring forth this essential cooperation for the understanding and eventual control of charcoal rot of sorghum.

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Questions

Maunder:
Should your reference to high-yield cultivars being super susceptible, referring to hybrids, not be better stated as first-cycle hybrids? The breeder has a tendency to place yield ahead of lodging, and this will be more dramatic in initial transition to hybrids. But in the case of U.S. sorghum history, after the first 8-10 years the problem with charcoal rot was greatly reduced.

Pande:
Yes, hybrids under Indian conditions are quite susceptible when planted in the postrainy season.

Schoeneweiss:
You stated that *Macrophomina phaseolina* does not grow in dead plant cells. Are you saying that the fungus does not grow as a saprophyte on organic matter derived from sorghum?

Pande:
Yes.

Vidyabhushanam:
It was stated that lodging is not the only criterion for measuring charcoal rot intensity. Is there any alternate measurement possible to know the level of incidence of the disease? Has any correlation between root and stalk rot infection been established?

Pande:
Lodging is the first apparent symptom of charcoal rot, and to confirm charcoal rot one has to split the plants to see the fungal colonization. Probably the two are necessary to assess the clear picture of charcoal rot.

Vidyabhushanam:
It is established that predisposition to drought stress is essential for charcoal rot. Is it clearly understood what stage and intensity of drought stress is required for the disease to manifest itself?

Pande:
I suppose moisture stress is the most important predisposing factor for charcoal rot infection and development. We do not know exactly at what stage the stress is effective. It seems stress at 50% flowering that continues up to maturity gives good charcoal rot expression.