Problems and Strategies in the Control of Downy Mildew

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Abstract

Downy mildew (DM) continues to be a major threat to pearl millet production in Africa and Asia. In India, heavy losses due to DM caused the withdrawal of several novel genotypes. Considerable progress has been made in the development of screening techniques and identification and utilization of host-plant resistance. The systemic fungicide metalaxyl has been highly effective in controlling infection by soil-, seed-, and airborne inoculum. Although variability in the pathogen, within and between continents has been demonstrated, sources of stable resistance have been identified. Cultivation of disease-resistant varieties, use of metalaxyl if resistance fails, coupled with roguing of infected plants are recommended for long-term control. Identification of durable resistance, basic genetic studies on the host and pathogen, and studies on the resistance mechanism(s) should be research priorities.

Résumé

Problèmes et stratégies de la lutte contre le mildiou : *Le mildiou reste une menace importante à la culture du mil en Afrique et en Asie. En Inde, plusieurs nouveaux génotypes ont été retirés de la production à cause des pertes considérables dues au mildiou. Cependant, le perfectionnement des techniques de criblage ainsi que l'identification et l'exploitation de la résistance des plantes-hôtes ont fait de grands progrès. Le fongicide systémique métalaxyl s'est montré très efficace pour maîtriser l'infection transmise par le sol, les semences ou le vent. Malgré la variabilité du pathogène à travers les continents, on a identifié des sources de résistance qui restent stables. Pour la lutte à long terme, on préconise l'utilisation des variétés résistantes et de métalaxyl en cas de non fonctionnement de la résistance, accompagnée de l'élimination des plantes atteintes par la maladie. Les priorités établies pour la recherche sont : l'identification d'une résistance durable, des études génétiques de base sur la plante-hôte et le pathogène et sur le(s) mécanisme(s) de résistance.*

Introduction

Downy mildew (DM), caused by *Sclerospora graminicola* (Sacc.) Schroet., is the most widespread and destructive pearl millet (*Pennisetum americanum*) disease. It is grown for grain and forage on about 26 million ha in the tropical and subtropical areas of Africa and the Indian subcontinent (FAO 1983). The disease has been reported in more than 20 countries (Safeeulla 1976) and is a major factor limiting the full exploitation of high-yielding improved cultivars in India. In India, DM epidemics caused substantial yield losses in F_1 hybrids from 1970-1976 (Safeeulla 1976), and again in 1983 and 1984 (S.D. Singh, ICRISAT and D.P. Thakur, Haryana Agricultural University, personal communication). Losses of 10-60% of the pearl millet harvest have also been reported in various African countries: Mozambique

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(Decarvalho 1949), Nigeria (King and Webster 1970), and Tanzania (Dogget 1970).

During the past decade progress has been made in understanding the biology and epidemiology of the disease, identifying host-plant resistance, and in developing alternative control measures. However, the disease continues to be a major problem. In this paper, the known control measures are summarized, and strategies and research priorities for long-term control are proposed.

History

S. graminicola was first reported on pearl millet in India by Butler (1907). Although the disease is established throughout most pearl millet-growing areas, higher disease incidence and losses were reported only in poorly drained, low-lying areas (Butler 1918, Mitra and Tandon 1930). Epidemics were never reported until 1970. With the traditional cultivars and cultivation methods, the disease remained sporadic. The discovery of cytoplasmic genetic male sterility in pearl millet (Burton 1958) encouraged the production of F_1 hybrids. Tift 23A, a male-sterile line from Georgia, USA, was imported and a hybrid breeding program began. The first pearl millet hybrid (HB 1) was released for commercial production in India in 1965, followed by HB 2 and HB 3. In 1971, a severe DM epidemic caused heavy losses (AICMIP 1973). This was followed by many epidemics (Safeeulla 1976, Thakur et al. 1978). In West Africa, the disease can reduce yields, although epidemics have not been reported.

"Breakdown" of Resistance: Causes and Consequences

In India "breakdown of resistance" primarily occurred in hybrids. All early hybrids were based on Tift 23A, which was bred in the USA in the absence of DM. After its introduction into India, neither this line nor the resultant hybrids were tested for disease susceptibility. No pearl millet diseases were important during that period, so the significance of *S. graminicola* was underestimated. With the large scale cultivation of these hybrids, the pathogen, which had been sporadic, began to multiply and gradually oosporic inoculum accumulated in the soil. With environmental conditions suitable for downy mildew and widespread cultivation of uniformly susceptible cultivars, severe and widespread DM epidemics began in 1971. Unfortunately, these hybrids continued to be cultivated despite their known susceptibility to DM (Pokhriyal et al. 1976).

There were three consequences of resistance breakdown: withdrawal of several of the hybrids, yield reductions, and an increase in the pathogen inoculum. After the introduction of HB 1 there was a gradual increase in pearl millet yields. HB 1 was replaced by HB 2 and later by HB 3. In 1970-71, India harvested a record grain production of 8 million t (AICMIP 1973). In 1971-72, a DM epidemic occurred and the yield dropped to 4.6 million t (Fig. 1). Following the epidemic some new cultivars were released and cultivated widely; however, total yield levels never reached the record 1970-71 level. The resultant oosporic inoculum build-up in the fields posed a major threat to the survival and continuation of even local cultivars, which were previously considered to be highly resistant.

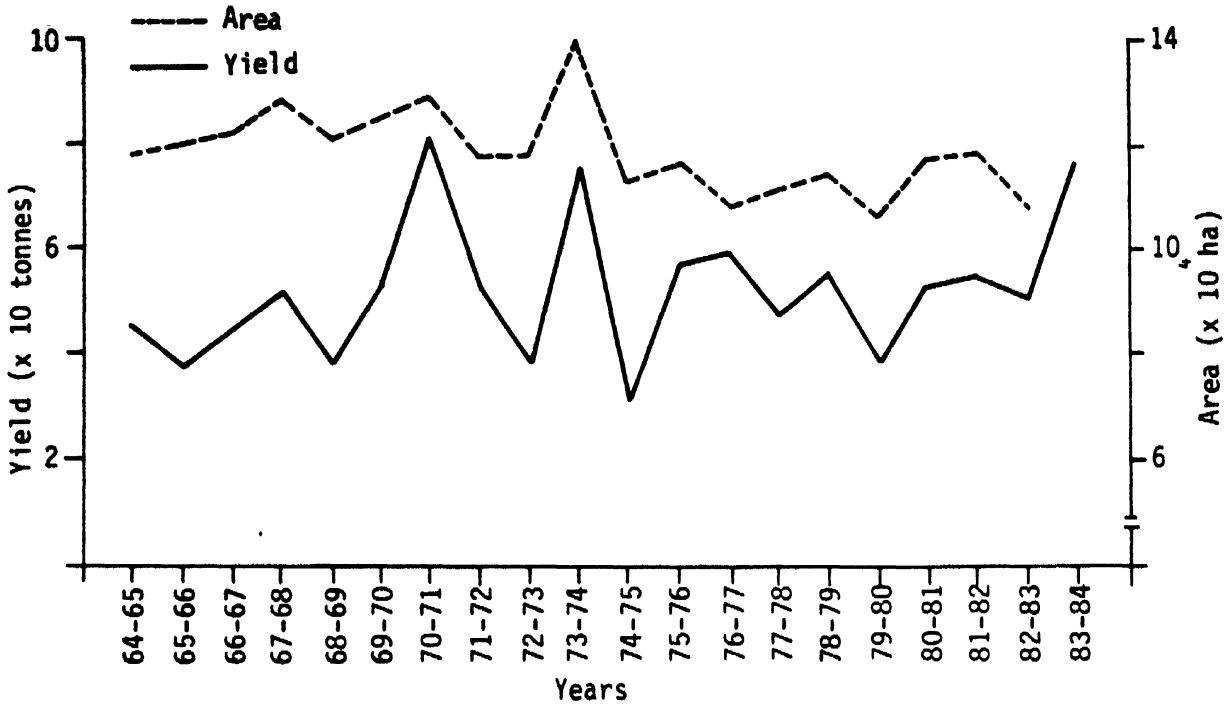
Pathogenic Variability

Pathotypes on Different Host Genera

The pathogen was first described as *Protomyces graminicola* on *Setaria verticillata* by Saccardo in 1876. It was renamed as *S. graminicola* by Schroeter in 1879 (Ullstrup 1973). The pathogen was reported on *S. viridis* by Farlow in 1884, and later on pearl millet and several other crops (Bhat 1973). However, the pathogen isolates infecting different hosts appear to be highly host-specific. For example, oospores from *S. italica* failed to infect pearl millet and vice versa, (Uppal and Desai 1932, Singh and Luther 1981). In another study, a pearl millet isolate from ICRISAT Center did not infect 23 hosts belonging to 11 genera previously reported as hosts (Singh and Williams 1979a). In one report, however, the pathogen from *S. italica* was reported to infect pearl millet and vice versa (Safeeulla 1976). Although these isolates may be morphologically similar, they do vai in pathogenicity. To clarify these differences, some nomenclatural changes, such as a *Setaria* pathotype and pearl millet pathotype, have been suggested to reflect the distinct pathogenic differences within this species (Williams 1982, 1984).

Variability on Pearl Millet

The first report of intervarietal differences in susceptibility to *S. graminicola* was made by Bhat (1973). He found that NHB 3, highly resistant at Mysore,



Source: Agricultural Situation in India

Figure 1. Pearl millet production in India (1965-84).

was highly susceptible at other places in India. Similar observations were made on other pearl millet genotypes by Girard (1975) in West Africa and by Shetty et al. (1981) in India. Support for differences in the susceptibility was provided by results from the International Pearl Millet Downy Mildew Nursery (IPMDMN), which has been evaluated annually since 1976. In these nurseries, certain entries were considerably more susceptible at some locations in West Africa than at locations in India, although there were also entries that possessed location nonspecific resistance (Table 1). To ascertain whether these differences were genetic or environmental, a project funded by the Overseas Development Administration (ODA) was initiated at the University of Reading. In a series of experiments conducted from 1980-1985 (Ball 1983, Ball and Pike 1983, Ball and Pike 1984, Idris and Ball 1984, and Ball et al. In press), collections of *S. graminicola* from West Africa proved quantitatively more pathogenic than those from India, and among West African collections, the collections from Nigeria were the most aggressive. This clearly supports the view that pathogenic variation exists in *S. graminicola*, and the differences are not just environmental.

Two more interesting reports on the variability in *S. graminicola* are available. Singh and Singh (In press) reported that NHB 3, which showed a high susceptibility at Durgapura, India, up to 1977, showed a high degree of resistance at this location after 1981, but at other locations in India it continues to be highly susceptible.

A different form of variability was demonstrated in a Zambian collection (Ball et al. In press). This collection was able to overcome the stunt reaction of BJ 104, which was exhibited by all other collections from West African countries and India.

The pathogen survives through the production of sexually produced oospores which are therefore genetic recombinants. Furthermore, it is heterothallic with two mating types (Michermore et al. 1983, Idris and Ball 1984). The pathogen populations, therefore, are dynamically variable and adaptable. However, many sources of stable resistance have been identified (ICRISAT 1985). Recently Ball et al. (In press) have provided evidence that one line, 111B, bred in India, after multiplication for two seasons in a downy mildew nursery in India was equally resistant to all collections, including some from West Africa. Further expansion of the multilocational testing program to identify stable resistance sources could be recommended.

Table 1. Differential and stable downy mildew reactions of certain entries in India and Nigeria.

	(Mean) Downy mildew score							
	Indian location[1]						Nigerian locations	
Entry	1	2	3	4	5	6	7	8
E 298-2-1-8	<1	0	0	0	<1	8	7	4
WC-8220	6	<1	0	2	<1	7	10	8
MPP-714-Sel 1	<1	3	2	4	<1	7	6	9
700780	1	<1	4	5	0	4	34	63
700792	2	0	2	3	0	4	32	54
700335	8	4	3	2	6	15	49	73
Mean[2]	2	3	3	3	3	11	24	22
7042 Susc. control	48	70	60	15	-	60	98	98

1. Locations: 1. Hisar 2. Jamnagar 3. Ludhiana 4. Pune 5. Patancheru 6. Mysore 7. Samaru and 8. Kano.
2. Location mean for entries.

Influence of Plant Maturity and Environment?

Environment and developmental stage of the host may influence the course of an epidemic. In a congenial environment, a severe epidemic may develop if an inoculum supply is available to young seedlings (Singh and Gopinath 1985). The senior author has seen disease-free crops of BJ 104 in some fields, while in other fields in the same area the crop was completely devastated by downy mildew. This may have been caused by the emergence of the crop at a time when there was a favorable environment and inoculum from an earlier crop was available. The disease-free crop may have emerged at a time when the environment was unsuitable for the production of sporangia. This could be one reason why BJ 104 has remained almost DM free in some parts of India, even though the cultivar is highly susceptible to infection by sporangia.

Control Measures

Control methods are designed to reduce soil- and seedborne oosporic inoculum and secondary spread within and among crops. The following methods have been used.

Cultural Controls

The basic principles of cultural control are sanitation and manipulation of the environment to the advantage of the host and disadvantage of the pathogen. Four techniques have been studied: sanitation, planting date, roguing, and nutrition.

Sanitation

Use of disease-free seed and management of infected debris after harvest are essential to reduce the primary inoculum in the field. Claims have been made that the disease is transmitted by internally seedborne mycelium (Sundaram et al. 1971, Shetty et al. 1977, Thakur and Kanwar 1977a), and also by oospores adhering to the seed surface (Thakur 1983). Although the internal seedborne nature of this disease is not entirely agreed upon by researchers, a procedure to prevent introduction of new variants of *S. graminicola* into India was devised jointly by the Indian Council of Agricultural Research (ICAR) and ICRISAT. In this process:

- seed is surface sterilized with $HgCl_2$ (0.1%) for 10 min followed by washing in several changes distilled sterile water,
- surface-sterilized seed is heated at 55°C for 10 min, and
- the seed is then treated with Metalaxyl at 2 g a.i. kg^{-1} seed.

This procedure, however, cannot be applied to larger seed quantities.

Collecting and burning infected leaf debris after harvest, or plowing to bury debris will help reduce oospore buildup in the soil. These practices, although effective, are not being used by farmers in India.

Early Planting

If the crop emerges at a time when conditions for the production of sporangia are unfavorable, or before sporangial inoculum levels have built up, for instance very early in the season, then the crop may escape infection, or have only a low disease incidence from infection by soilborne oospores. Conversely, a crop planted when sporangia are abundant will be severely affected (Chahal et al. 1978b). However, because of the unpredictability of environmental conditions following late planting, adjusting the planting date to avoid high DM pressure is an impractical control method.

Roguing

No collateral hosts are known to harbor *S. graminicola* which attacks pearl millet. Therefore the removal and destruction of DM-infected plants can reduce the spread of disease-causing sporangial inoculum within the same season (Thakur and Kanwar 1977b, Singh and Williams 1980) and oospore buildup in the soil for following seasons. Roguing infected plants prior to oospore formation has been recommended (Kenneth 1977, Thakur 1980). This practice is used to control *Peronosclerospora maydis* in South Sumatra (Tantera 1975), and DM on sugarcane and maize in Taiwan (Sun et al. 1976).

In the absence of collateral hots, roguing could provide effective control. However, success will depend on the willingness and cooperation among farmers, timely availability of labor, expertise in identifying diseased plants at an early stage, and governmental support.

Nutrition

Research on the possible relationship between downy mildew infection and nitrogen or phosphorus, added to either the soil or plants, has produced contradictory data. (Deshmukh, et al. 1978a, Singh 1974, Singh and Agarwal 1979) Further work, with soil analyses prior to fertilization, is necessary.

Chemical Controls

Systemic as well as nonsystemic fungicides have been used. Because the disease is seedborne, soilborne, or airborne, fungicides have been applied to seed, soil, and growing plants.

Nonsystemic Fungicides

Trials resulted were contradictory; some workers hae obtained positive results (Suryanarayana 1965; Thakur and Kanwar 1977c; AICMIP 1970-1976), while others failed to obtain good control (Ramakrishnan 1963, Singh 1974). The reasons for failure of protective fungicides were their inability to control systemic growth of the pathogen, to withstand frequent rains, and to protect enlarging roots and plumules from oospore infection after their application to seed.

Systemic Fungicides

A new era for chemical control of oomycete fungi began with the acylalanine fungicides (Urech et al. 1977). Seed treatment with metalaxyl at 1-2 g a.i. kg^{-1} of seed has given excellent control of DM in maize, sorghum, and pearl millet (Venugopal and Safeeulla 1978, Exconde and Molina 1978, Frederiksen 1979, Schwinn 1980, Williams and Singh 1981, Singh 1983b, Dang et al. 1983). As a seed treatment, it controls soil- and seed-carried inoculum, and is absorbed by the seedlings, protecting them from sporangial infection. In highly tillering crops like pearl millet, however, the efficacy of the fungicide is reduced as plants grow. Foliar applications of metalaxyl have cured diseased plants (Singh and Williams 1979b, Singh et al. 1984).

Metalaxyl at 31 ppm a.i. cured greenhouse plants, but a higher concentration was needed for field-grown plants. Although plant age did not affect recovery, head length was reduced if diseased plants were sprayed prior to panicle development (Singh et al. 1984).

Limitations to Metalaxyl Use

Phytotoxic effects of metalaxyl seed treatment expressed as reduced seed germination have been demonstrated; however, only at higher than recommended rates of application, e.g., >2 g a.i. kg^{-1} of seed (Singh 1983b). Cultivars differ in their sensitivity. The seed treatment formulation (SD 35) is particularly toxic. It is suggested, therefore, that cultivars be evaluated for their sensitivity prior to large-scale seed treatment.

Metalaxyl may become ineffective with time probably because of its narrow spectrum of activity. There are already reports of a decline in its effective-

ness against certain Phycomycetes (Reuveni et al. 1980, Bruin and Edgington 1981).

Host-Plant Resistance

Use of resistant cultivars is the best method to control this disease. Considerable progress has been made in the development of screening techniques, identification of sources of resistance, and breeding of resistant cultivars.

Screening Techniques

Field screening. A field screening technique that mainly utilizes sporangia as the infection propagules has been developed (Williams et al. 1981). This technique has three components:

- infector rows (inoculum donors) planted in advance as a mixture of 2-3 susceptible genotypes;
- test rows planted after 40-50% plants in the infector rows develop the disease; and
- indicator rows (susceptible genotype) which indicate the level of disease pressure.

Perfo-spray irrigation is applied in the early evening as needed to encourage high night-time relative humidity for sporangial production and infection, especially during early growth of test material. The technique was developed:

- to provide uniform inoculum distribution,
- to inoculate naturally throughout the susceptible period,
- to minimize chances of escape,
- to utilize both types of inocula (oospores and sporangia), and
- to provide opportunities for breeding activities in the same season, field, or both.

This technique is being used twice a year at the ICRISAT Center and has been adopted by many researchers in India and West Africa. Some of the resistant sources identified using this technique have been stable across hot-spot locations in India and West Africa.

Laboratory Screening. To detect escapes from field screening and to conduct pathological studies, various laboratory and greenhouse inoculation techniques, have been developed. Singh and Gopinath (1985) described one such technique: potted seedlings in the coleoptile stage (<10 mm above ground) are inoculated using a microsyringe. A drop of inoculum placed at the tip of the seedling flows down to the base covering most of the above-ground surface area. The inoculated seedlings are marked to differentiate them from those that may emerge later. Under favorable conditions, >90% of the susceptibility of a genotype is expressed within 15 d after inoculation.

Sources of Resistance

At ICRISAT Center, 3163 accessions from the Genetic Resources Unit originating from more than 20 countries in the major millet growing areas of the world were screened. A total of 428 accessions with high levels of resistance and which flowered in 45-60 d at ICRISAT Center, were further evaluated, a 48 single plant selections made. Progenies of th were highly resistant and agronomically acceptable. These selections will serve as the major source of DM resistance for future breeding in India. In addition, many sources of resistance have been identified in India by other workers (Chahal et al. 1975, Dass and Kanwar 1977, Chahal et al. 1978a, Deshmukh et al. 1978b, Appadurai et al. 1978, Shinde and Utikar 1978, Thakur and Dang 1985).

Sources of Stable Resistance. With the help of the cooperators in India and West Africa, the IPMDMN began in 1976. Each year 45 entries from breeders and pathologists are evaluated at DM hot-spot locations in India and Africa. More than 50 sources of stable resistance, primarily originating in Nigeria, have been identified (Table 2).

Utilization of Resistance

At ICRISAT Center resistant sources are being utilized, particularly in the hybrid program. SDN 503, P 7, 700516, P 310, and 700651 are being used in the pollinator project, while resistance from P 7 and 700651 is being transferred into hybrid seed parents. Figure 2 shows the basic scheme for the identification and utilization of resistance.

In the population improvement project, progenies of composites are tested and selected in the DM nursery. The levels of DM resistance in the composites have increased substantially, so incorporation of resistance from other sources is currently not

Table 2. Downy mildew (DM) reactions of 26 entries and standard susceptible controls included in the IPMDMN trial for 2-9 years and at all locations of testing in India and Africa.

Entry	Origin	Mean DM severity (%)								
		1976	1977	1978	1979	1980	1981	1982	1983	1984
SDN 503	Nigeria	1	1	3	3	8	9	8	1	2
P 7	Mali	6	2	3	3	9	6	6	3	3
700251	Nigeria	3	2	2	1	9	6	6	4	-
700516	Nigeria	2	3	2	1	7	5	3	3	-
700651	Nigeria	1	3	4	1	10	6	4	3	-
SDN 347-1	Nigeria	5	3	4	3	-	-	-	-	-
BJ 104	New Delhi	-	14	-	13	21	10	17	-	-
EB 18-3-1	ICRISAT	-	-	2	1	7	2	-	-	-
IP 1930	ICRISAT	-	-	-	2	8	2	1	2	2
EB 83-2	ICRISAT	-	-	-	2	6	5	3	4	1
MPP 7147-2-1	New Delhi	-	-	-	1	7	5	6	4	4
E 298-2-1-8	ICRISAT	-	-	-	-	5	3	4	3	1
700546	Nigeria	-	-	-	-	7	6	7	5	1
700512	Nigeria	-	-	-	-	6	3	3	5	4
714	Nigeria	-	-	-	-	6	6	4	5	-
IP 2058	Nigeria	-	-	-	1	9	8	5	-	-
P 310-17	Mali	-	-	-	-	-	-	-	1	1
P 472-1	Mali	-	-	-	-	-	-	-	1	2
P 473-4	Mali	-	-	-	-	-	-	-	3	1
P 2672-6	Niger	-	-	-	-	-	-	-	4	3
IVC-P 78-2	ICRISAT	-	-	-	-	-	-	-	6	1
IVC-P 8004-2	ICRISAT	-	-	-	-	-	-	-	8	2
NELC-H79-4 (Original)	ICRISAT	-	-	-	-	-	-	-	6	3
SSC-BB 78-4 (Reconstituted)	ICRISAT	-	-	-	-	-	-	-	2	2
(B 282 × 3/4 E B-100) -11-9-2-2	ICRISAT	-	-	-	-	-	-	-	6	1
(F4FC 1436-4-3-2 × J104 ST)-1-1-5)	ICRISAT	-	-	-	-	-	-	-	8	1
Location mean for entries		-	9	7	5	4	11	6	7	6
Suceptible controls										
7042	Chad	-	-	-	58	63	68	44	64	44
1593	Jamnagar	-	28	14	8	17	15	-	-	-

needed. Two open pollinated varieties, WC-C75 and ICMS 7703, have been released for cultivation in India. WC-C75 has been cultivated by Indian farmers since 1982, and is now grown in nine states on several hundred thousand ha. There is yet no report of its resistance becoming ineffective.

Development of Resistance

Susceptibility to DM gradually builds up if a cultivar is grown for several years. In the past, several pearl millet cultivars were withdrawn in India because of their susceptibility to DM. Research at ICRISAT Center has shown that such cultivars could be resurrected by selecting for resistance from variability within the lines. This was demonstrated in a landrace from Chad in 1982 (Singh, ICRISAT, personal communication) and also for parents of hybrid BJ 104 (Singh 1983a). Lines thus selected have shown high levels of DM resistance at several locations in India (Table 3). The selected parental lines (841A and ICMP 84814) of BJ 104 are phenotypically sim-

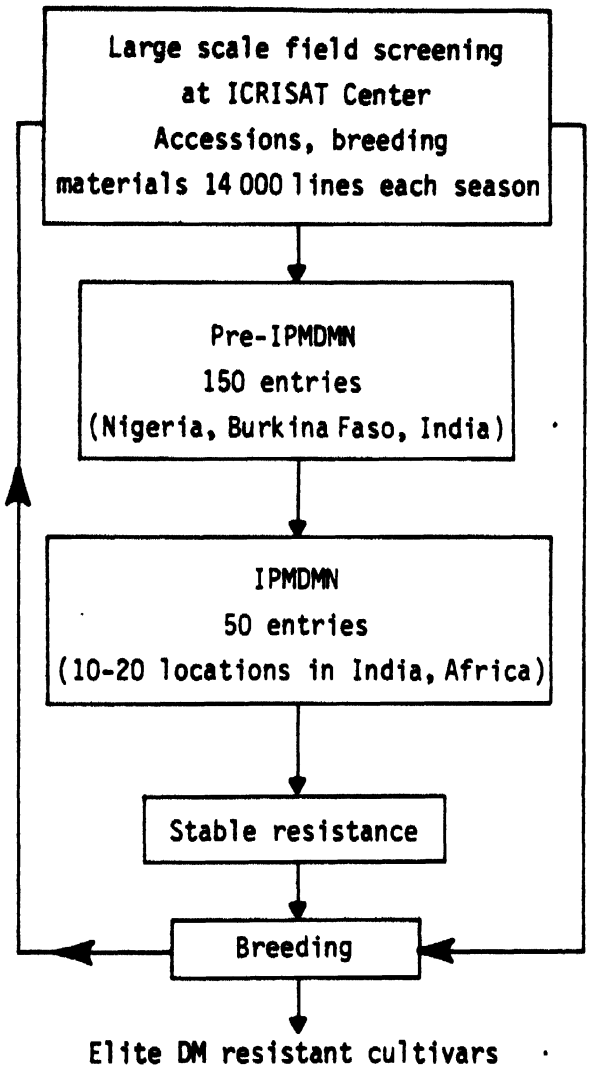


Figure 2. Basic scheme for the identification and utilization of downy mildew resistance.

Table 3. Downy mildew (DM) reactions of three lines reselected for DM resistance at several locations[1] in India.

Entry	Test year	DM severity (%) locations[1] 1	2	3	4	5	6	7	8	9
241A1	1983	0	0	0	0	0	0	<1	9	-
ICMP 84814	1984	12	0	1	-	-	2	8	13	3
7042	1982	11	-	0	0	4	7	4	9	0
7042[2]	-	64	4	33	30	63	92	57	67	52

1. Locations: 1. Aurangabad 2. Durgapura 3. Jamnagar 4. Coimbatore 5. Hisar 6. Patancheru 7. Ludhiana 8. Mysore 9. Kovilpatti
2. Mean of 3 test years.

iliar to the original parental lines and the hybrid (ICMH 84814) based on these lines is similar in yield and other characteristics to BJ 104 (Table 4). However, 841A differs significantly from 5141A for several characters, most notably for time to 50% flowering, height, head length, and individual grain mass (Table 4).

Inheritance of Resistance

Little is known about the model of inheritance (Nene and Singh 1976). In some cases the resistance was demonstrated to be controlled by one or two dominant genes (Appadurai et al. 1975, Singh 1974, Gill et al. 1975, Gill et al. 1978), while in others it was reported to be controlled polygenically and by additive and nonadditive gene effects (Singh et al. 1978, Basavaraj et al. 1980, Shinde et al. 1984). The overall mode of inheritance is unclear because the parents used in these studies were heterozygous, the pathogen populations were highly variable, and inoculation procedures were generally not standardized.

Homozygous parents for susceptibility and resistance and uniform inoculum should be used in inheritance studies. Laboratory screening such as the newly-developed, seedling-inoculation technique (Singh and Gopinath, 1985) will be useful.

Strategies for Control

Availability of resistant cultivars, an effective systemic fungicide, and cultural practices provide opportunities for the long-term management of this disease.

Host-Plant Resistance

Growing one cultivar over a large area should be avoided. Cultivars should be specified for particular areas, and there should be several cultivars in given areas. Success, however, will depend on the genetic differences among the cultivars. Another approach would be to use gene deployment over time. This approach is based on the principle of host specificity. It is likely that pathogenicity and consequently the oospore population of the pathogen may increase if a genotype is grown for a long period. Conversely, the pathogenicity may decline if the specific host is withdrawn from cultivation. This particular phenomenon has been observed with NHB 3, at Durgapura in Rajasthan (Singh and Singh In Press).

Table 4. Comparison of BJ 104 and 5141A with their downy-mildew resistant counterparts, ICMH 84814, and 841A, ICRISAT Center, rainy season 1985.

Entry	Tillering (no)	Time to 50% flowering (d)	Plant height (cm)	Head length (cm)	Head mass (kg ha^{-1})	1000 grain mass (g)	Grain yield (kg ha^{-1})
ICMH 84814	2.8	44	127	15.9	2800	6.9	2100
BJ 104	3.8	42	111	16.3	3000	6.5	2100
841A	3.1	53	106	15.0	1600	5.8	1100
5141A	3.3	51	96	11.5	1600	4.9	1000
Mean[1]	2.4	44.4	120.0	15.8	3000	6.8	2100
S.E.	±0.2	±0.5	±2.1	±0.4	±275	±0.22	±200

1. Mean of 17 entries including 13 reconstituted hybrids that were evaluated in the trial.

Open-pollinated cultivars in which every individual is genetically different provide another opportunity to keep the disease under control. Due to their [rogeneity, such cultivars will have a buffering [t against DM. They are unlikely to be disease-free, but they will not develop the disease in epidemic proportions for several years. ICRISAT is putting major emphasis on open-pllinated varieties. In Africa, where hybrids are not currently being grown for various reasons, open-pollinated cultivars will be the most appropriate genotypes for DM control.

Fungicides

Metalaxyl is a powerful tool to control DM in pearl millet. Although the inefficacy of metalaxyl has been reported for some other diseases, it can still be used effectivewly for control of downy mildew of pearl millet if the strategies for its use are carefully worked out. The best strategy would be to keep the fungicide in reserve, for use only if the resistance breaks down unexpectedly.

ıltural practices

Of the many cultural practices known, only roguing infected plants soon after their detection is strongly recommended. This should be done even if other control methods, including resistant cultivars, have been used.

Research Priorities

Durable Resistance

Cultivation of varieties over a large area for many years is the only method to detect the durability of resistance. Stability (multilocational tests), has been suggested as one method which might predict durability (Johnson 1984), but which whould need testing over time. Moreover, durable resistance to systemic diseases like DM in which a plant can be either diseased or healthy, should be viewed differently from leaf spots and rusts. Therefore, to make the resistance durable, a system must be identified in which the pathogen can parasitize each plant without adversely affecting its yield.

Basic Genetic Studies

With the available knowledge of variation in the pathogen population, frequencies of virulence genes need to be assessed. Likewise genes for resistance in the host should be determined. To utilize the identified resistance by the appropriate breeding procedures, the pattern of inheritance should be studied.

Nature of Resistance

Resistance may operate before or after penetration. During the prepentration stage, spore germination may be inhibited due to certain chemicals, or there may be barriers to penetration by mechanical or physiological factors. After penetration, several factors, including incompatability, reduced colonization, and sporulation (slow mildewing) may stop and/or delay disease development. All these aspects need to be studied. Research is needed to identify lines with reduced colonization and sporulation, and to further improve these traits by appropriate selection methods.

References

AICMIP (All India Coordinated Millet Improvement Project). 1970-1976. Progress reports 1971-75. New Delhi, India: Indian Council of Agricultural Research.

Appadurai, R., Parambaramani, C., and Natarajan, U.S. 1975. Note on the inheritance of susceptibility of pearl millet to downy mildew. Indian Journal of Agricultural Sciences 45(4):179-180.

Appadurai, R., Subramanian, R., Parambaramani, C., and Purushothaman, S. 1978. Development of disease resistant pearl millet (*Pennisetum typhoides* (Burm. F.) Stapf & Hubb.). Madras Agricultural Journal 65(1):14-16.

Ball, S.L. 1983. Pathogenic variability of downy mildew (*Sclerospora graminicola*) on pearl millet. I. Host cultivar reactions to infection by different pathogen isolates. Annals of Applied Biology 102:257-264.

Ball, S.L., and Pike, D.J. 1983. Pathogenic variability of downy mildew (*Sclerospora graminicola*) on pearl millet. II. Statistical techniques for analysis of data. Annals of Applied Biology 102:265-273.

Ball, S.L., and Pike, D.J. 1984. Intercontinental variation of *Sclerospora graminicola*. Annals of Applied Biology 104:41-51.

Ball, S.L., Pike, D.J., and Burridge C.Y. (In press). Characterization of populations of *Sclerospora graminicola*. Annals of Applied Biology.

Basavaraj, R., Safeoulla, K.M., and Murty, B.R. 1980. The role of gene effects and heterosis for resistance to downy mildew in pearl millet. Indian Journal of Genetics and Plant Breeding 40(3):537-548.

Bhat, S.S. 1973. Investigations on the biology and control of *Sclerospora graminicola* on bajra. Ph.D. thesis, University of Mysore, Mysore, Karnataka, India. 165 pp.

Bruin, G.C.A., and Edgington, L.V. 1981. Adaptive resistance in Peronosporales to metalaxyl. Canadian Journal of Plant Pathology 3:201-208.

Burton, G.W. 1958. Cytoplasmic male-sterility in pearl millet (*Pennisetum glaucum*) (L.) R. Br. Agronomy Journal 50:230-231.

Butler, E.J. 1907. Some diseases of cereals caused by *Sclerospora graminicola*. Memoirs of the Department of Agriculture in India. Botanical Series 2:1-24.

Butler, E.J. 1918. Fungi and disease in plants. Calcutta, India: Thacker, Spink & Co. pp. 218-223.

Chahal, S.S., Gill, K.S., Phul, P.S., and Aujla, S.S. 1975. Screening of the pearl millet germplasm for the greenear disease caused by *Sclerospora graminicola* (Sacc.) Schroet. Crop Improvement 2:65-70.

Chahal, S.S., Gill, K.S., and Phul, P.S. 1978a. Note on the reaction of pearl millet inbreds against the downy mildew pathogen. Indian Journal of Agricultural Sciences 48:190-191.

Chahal, S.S., Gill, K.S., and Phul, P.S. 1978b. Relationship between the date of sowing and incidence in pearl millet *Pennisetum typhoides* in the Punjab State. Crop Improvement 5:165-166.

Dang, J.K., Thakur, D.P., and Grover, R.K. 1983. Control of pearl millet downy mildew caused by *Sclerospora graminicola* with systemic fungicides in an artificially contaminated plot. Annals of Applied Biology 102:99-106.

Dass, S., and Kanwar, Z.S. 1977. Screening and evaluation of pearl millet male-sterile lines, pollinators and their F_1's for downy mildew resistance. Indian Journal of Agricultural Sciences 47(6) :296-298.

DeCarvalho, T. 1949. O mildio de milho (*Sclerospora* spp.). (In Pt.) Gazeta do Agriculture Mozambique 1:61-63.

Deshmukh, S.S., Mayee, C.D., and Kulkarni, B.S. 1978a. Reduction of downy mildew of pearl millet with fert[illegible] management. Phytopathology 68:1350-1353.

Deshmukh, H.G., More, B.B., and Utikar, P.G. 1978b. Screening germplasm of pearl millet against downy mildew (*Sclerospora graminicola* (Sacc.) Schroet.). Indian Journal of Agricultural Research 12(2):85-88.

Doggett, H. 1970. Downy mildew in East Africa. Indian Phytopathology 23:350-355.

Exconde, O.R., and Molina, A.B. 1978. Ridomil (Ciba Geigy) : a seed dressing fungicide for the control of Philippine corn downy mildew. Philippine Journal of Crop Science 3:1-5.

Farlow, W.G. 1984. Addition to the *Peronosporaceae* of the United States. Botanical Gazette 9:37-40.

FAO. 1983. 1982 FAO Production Yearbook Vol. 36. Rome, Italy: FAO.

Frederiksen, R.A. 1979. Chemical control of sorghum downy mildew. Sorghum Newsletter 22:129.

Gill, K.S., Phul, P.S., Singh, N.B., and Chahal, S.S. 1975. Inheritance of resistance to downy mildew in pearl millet[illegible] a preliminary report. Crop Improvement 2:128-129.

Gill, K.S., Phul, P.S., Chahal, S.S., and Singh, N.B. 1978. Inheritance of resistance to downy mildew disease in pearl millet. Cereal Research Communications 6(1):71-74.

Girard, J.C. 1975. Downy mildew of pearl millet in Senegal. Pages 59-73 *in* Proceedings of Consultants' Group Meetings on Downy Mildew and Ergot of Pearl Millet, 1-3 Oct 1975, ICRISAT, Hyderabad, India. Patancheru, A.P. 502 324, India: International Crops Research Institute for the Semi-Arid Tropics.

ICRISAT (International Crops Research Institute for the Semi-Arid Tropics). 1985. Report of the 1984 International Pearl Millet Downy Mildew Nursery (IPMDMN). Progress Report, MP-112. Patancheru, A.P. 502 324, India: ICRISAT. (Limited Distribution.)

Idris, M.O., and Ball, S.L. 1984. Inter- and intra-continental sexual compatability in *Sclerospora graminicola*. Plant Pathology 33:219-223.

Johnson, R. 1984. A critical analysis of durable resistance. Annual Review of Phytopathology 22:309-330.

Kenneth, R. 1977. *Sclerospora graminicola* (Sacc.) Schroet. Pages 96-99 *in* Diseases, pests and weeds in tropical crops (Kranz, J., Schmutterer, H., and Koch. W., eds.) Berlin, Federal Republic of Germany: Verlag Paul Parey.

King, S.B., and Webster, O.J. 1970. Downy mildew of sorghum in Nigeria. Indian Phytopathology 23:342-349.

Michelmore, R.W, Pawar, M.N., and Williams, R.J. 1982. Heterothallism in *Sclerospora graminicola*. Phytopathology 72:1368-1372.

.H., and Tandon, R.N. 1930. A note on *Sclerospora graminicola* (Sacc.) Schroet. in Allahabad. Journal of the Indian Botanical Society 9:243.

Nene, Y.L., and Singh, S.D. 1976. Downy mildew and ergot of pearl millet. PANS 22:366-385.

Pokhriyal, S.C., Unnikrishnan, K.V., Singh B., Dass, R., and Patil, R.R. 1976. Combining ability of downy mildew resistant lines in pearl millet. Indian Journal of Genetics and Plant Breeding 36:403-409.

Ramakrishnan, T.S. 1963. Diseases of millets. New Delhi, India: Indian Council of Agricultural Research.

Reuveni, M., Eyal, H., and Cohen, Y. 1980. Development of resistance to metalaxyl in *Pseudoperonospora cubensis*. Plant Disease 64:1108-1109.

Safeeulla, K.M. 1976. Biology and control of the downy mildews of pearl millet, sorghum, and finger millet. Mysore, Karnataka, India: University of Mysore. 304 pp.

Schwinn, F.J. 1980. Prospects for chemical control of the cereal downy mildews (Williams, R.J., Frederiksen, R.J., hogho, L.K., and Bengston, G.D, eds.). Pages 220-222 in Sorghum diseases : a world review: proceedings of the International Workshop on Sorghum Diseases, 11-15 Dec 1978, ICRISAT Center, India. Patancheru, A.P. 502 324, India: International Crops Research Institute for the Semi-Arid Tropics.

Shetty, H.S., Neergaard, P., and Mathur, S.B. 1977. Demonstration of seed-transmission of downy mildew or green ear disease, *Sclerospora graminicola* in pearl millet (*Pennisetum typhoides*). Proceedings of the Indian National Science Academy, B 43:201-205.

Shetty, H.S., and Ahmad, R. 1981. Physiologic specialization in *Sclerospora graminicola*. Indian Phytopathology 34(3):307-309.

Shinde, P.A., and Utikar, P.G. 1978. Screening of local selections of pearl millet for resistance to downy mildew. Indian Phytopathology 31:224-225.

Shinde, R.B., Patil, F.B., and Sangave, R.A. 1984. Resistance to downy mildew in pearl millet. Journal of Maharashtra Agricultural Universities 9(3):337-338.

Singh, F., Singh, R.K., Singh, R.M., and Singh, R.B. 1978. Genetic analysis of downy mildew (*Sclerospora graminicola*) resistance in pearl millet (*Pennisetum typhoides* (Burm.) S. & H.) Zeitschrift fuer Pflanzenzuechtung 81:54-57.

Singh, P., and Agarwal, R.K. 1979. Effect of zinc and phosphatic fertilizers on the incidence of downy mildew and the nutrient contents in pearl millet. Indian Journal of Agricultural Sciences 49:459-462.

Singh, S.D. 1974. Studies on the downy mildew disease (*Sclerospora graminicola* (Sacc.) Schroet.) of bajra (*Pennisetum typhoides* (Burm. F), Stapf and C.E Hubb.) Ph.D thesis, Indian Agricultural Research Institute, New Delhi, India. 126 pp.

Singh, S.D. 1983a. Selection for downy mildew resistance in the parental lines of the susceptible hybrid BJ 104. International Working Group on Graminaceous Downy Mildews (IWGGDM) Newsletter 5(1):2.

Singh, S.D. 1983b. Variable cultivar response to Metalaxyl treatment in pearl millet. Plant Disease 67:1013-1015.

Singh, S.D., and Gopinath, R. 1985. A seedling inoculation technique for detecting downy mildew resistance in pearl millet. Plant Disease 69:582-584.

Singh, S.D., Gopinath, R., Luther, K.D.M, Reddy, P.M., and Pawar, M.N. 1984. Systemic remissive properties of Metalaxyl against downy mildew in pearl millet. Plant Disease 68:668-670.

Singh, S.D., and Luther, K.D.M. 1981. Further studies on the host range of *Sclerospora graminicola*. International Working Group on Graminaceous Downy Mildews (IWGGDM) Newsletter 3(2):3-4.

Singh, S.D., and Singh, G. (In press.) Resistance to downy mildew in pearl millet hybrid NHB 3 at Durgapura. Indian Phytopathology.

Singh, S.D., and Williams, R.J. 1979a. A study of the host range of *Sclerospora graminicola*. International Working Group on Graminaceous Downy Mildews (IWGGDM) Newsletter 1(2):3.

Singh, S.D., and Williams, R.J. 1979b. Downy mildew cure by Ridomil and its control by Apron. International Working Group on Graminaceous Downy Mildews (IWGGDM) Newsletter 1(2):3.

Singh, S.D., and Williams, R.J. 1980. The role of sporangia in the epidemiology of pearl millet downy mildew. Phytopathology 70:1187-1190.

Sun, M.H., Chang, S.S., and Tsang, C.M. 1976. Research advances in sugarcane downy mildew of corn in Taiwan. Kasetsart Journal 10:89-93.

Sundaram, N.V., Ramasastry, D.V., and Nayar, S.K. 1973. Note on seed-borne infection of downy mildew (*Sclerospora graminicola* (Sacc.) Schroet.) of pearl millet. Indian Journal of Agricultural Sciences 43:215-217.

Suryanarayana, D. 1965. Studies on the downy mildew diseases of millets in India. Bulletin, Indian Phytopathological Society 3:72-78.

Thakur D.P. 1980. Utilization of downy mildew resistant germplasms and other resources for increased productivity of pearl millet under arid and semi arid regions of India. Annals of Arid Zone 19(3):265-270.

Thakur, D.P. 1983. Quantum of oosporic seed load of *Sclerospora graminicola* on pearl millet downy mildew. Pages 43-44 *in* Advancing frontiers: Plant Sciences 1983 : proceedings of the National Symposium on Advancing Frontiers in Plant Sciences, 26-30 Nov 1983, Jodhpur, India (Arya, H.C., Sankhla, N., Tewari, M.N., Shekhawat, N.S., and Purohit, S.D., eds.). Jodhpur, Rajasthan, India: Scientific Publishers.

Thakur, D.P., and Dang J.K. 1985. Breeding for disease resistance in pearl millet. Presented at the All India Coordinated Millets Improvement Project Workshop, 26-29 Apr 1985, Mahatma Phule Agricultural University, Rahuri, Maharashtra, India.

Tantera, D.M. 1975. Cultural practices to decrease losses due to corn downy mildew disease. Tropical Agricultural Research Series 8:165-173.

Thakur, D.P., and Kanwar, Z.S. 1977a. Internal seed-borne infection and heat therapy in relation to downy mildew of *Pennisetum typhoides* Stapf and Hubb. Science and Culture 43:432- 434.

Thakur D.P., and Kanwar, Z.S. 1977b. Infectivity of sporangia of *Sclerospora graminicola* on pearl millet downy mildew. Indian Journal of Mycology and Plant Pathology 7(1):104-105.

Thakur D.P., and Kanwar, Z.S. 1977c. Reducing downy mildew (*Sclerospora graminicola*) of pearl millet (*Pennisetum typhoides*) by fungicidal seed and soil treatments. Pesticides 11(8):53-54.

Thakur D.P., Kanwar, Z.S., and Maheshwari, S.K. 1978. Effect of downy mildew/green ear disease (*Sclerospora graminicola* (Sacc.) Schroet.) on yield and other plant characters of bajra (*Pennisetum typhoides* (Burm.f) Stapf & Hubb.). Haryana Agricultural University Journal of Research 8:82-85.

Ullstrup, A.J. 1973. An overview of the downy mildews of corn and sorghum. Report of a workshop on the downy mildews of sorghum and corn. Technical Report, Texas Agricultural Experimental Station, Department of Plant Sciences 74-1:5-12.

Uppal, B.N., and Desai, M.K. 1932. Physiological specialization in *Sclerospora graminicola* (Sacc.) Schroet. Indian Journal of Agricultural Science 2:667-678.

Urech, P.A., Schwinn, F.J., and Staub, T. 1977. CGA 48988, a novel fungicide for the control of late blight, downy mildews, and related soil-borne diseases. Pages 623-631 *in* Proceedings of the Ninth British Insecticide and Fungicide Conference, 21-24 Nov 1977, Brighton, UK. Vol. 2. London, UK: British Crop Protection Council.

Venugopal, M.N., and Safeeulla, K.M. 1978. Chemical control of downy mildews of pearl millet, sorghum and maize. Indian Journal of Agricultural Sciences 48:537-539.

Williams, R.J. 1982. Proposals on the use of pathotypes. International Working Group on Graminaceous Downy Mildews (IWGGDM) Newsletter 4(1):6.

Williams, R.J. 1984. Downy mildews of tropical cereals. Advances in Plant Pathology 2:1-103.

Williams, R.J., and Singh, S.D. 1981. Control of pearl millet downy mildew by seed treatment with M[illegible] Annals of Applied Biology 97:263-268.

Williams, R.J., Singh, S.D., and Pawar, M.N. 1981. An improved field screening technique for downy mildew resistance in pearl millet. Plant Disease 65:239-241.