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Efficient Management of Resources for Sustainable Crop Production in Arid Region

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Abstract : In this bulletin, results of several laboratory and field experiments conducted on the use of crop sequences, crop residues and limited water for maximizing crop productivity in low rainfall region are presented and discussed. This work was carried out largely under a Indo-US project "Enhancing fertilizer use efficiency in conjunction with residue management in dry land crops and cropping systems in low rainfall conditions". Utilizing available resources, some low input technologies were developed for maximizing crop productivity in the arid regions.

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Cover : Mustard residues in a farmer's field.

Research bulletin

Efficient Management of Resources for Sustainable Crop Production in Arid Region

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Foreword

Projections on population and food requirements show that by the end of ninth five year plan, India will have to produce around 230 Mt of food grains. Since the potential of irrigated area expansion is limited, most of the drylands are faced with the challenges of producing more per unit land with uncertain and dwindling supplies of water. To improve productivity levels of rainfed crops from 904 to 2000 kg ha^{-1}, besides adoption of high yielding varieties a substantial rise in nutrient inputs will be necessary. At this productivity level, soil will be deprived of 30 Mt of nutrients annually which can not be restored from fertilizers alone due to their limited availability, high cost, risks involved and associated environmental problems. In order to sustain the soil productivity and yield levels, there is a need of evolving eco-friendly technologies by efficient management of available resources of economically poor rainfed farmers.

Realizing the importance of this problem, and the need of the region, Indo-US Sub-Commission on Dryland Agriculture granted a collaborative project on enhancing soil productivity of dryland region. This project has been in operation at the Central Arid Zone Research Institute, Jodhpur since 1990. The work done, by multidisciplinary team of scientists, on crop residues management, cropping systems and water management for enhancing soil productivity for the over one decade reflected in this bulletin is commendable. I am sure this bulletin will be a useful guide for research and extension workers as a reference material for disseminating low input technologies for sustainable agriculture to the farming community of dry regions.

G.B. Singh

Preface

The Indian agriculture scenario shows that the region has almost come to physical frontiers with regard to horizontal expansion of area under agriculture. It is estimated that country may need around 300 Mt of food grain by 2025 if the present trend of population growth is unabated. Thus, we are left with only one option of vertical expansion for enhancing productivity. The country has still large unexploited potential to meet the ever increasing food needs. This potential has to be exploited from the dryland areas mainly, which would still constitute about 80 Mha out of the total cultivable area of 142.5 Mha in spite of extending the area under irrigation. However, at present the productivity levels in dryland region are quite low due to nutrients and moisture stresses. But use of fertilizers alone even at optimum levels in these risk prone areas cannot meet the challenge of food grain target. More so, the demand and supply scenario of fertilizer nutrients also show a gap of 10 Mt annually. The risk with fertilizer application in moisture deficit regions along with gap in availability can only be compansated from organic manures, crop residues, biofertilizers and selection of better crop sequences.

Thus in dry areas, constraint to productivity can be overcome by proper soil, water and pest management technologies evolved with location specific research. To develop the appropriate strategy for meeting this challenge, one has to analyse the situation of land, water, fertilizer, organic manure and pest and disease incidences in relation to crops and cropping sequences. In this bulletin, a modest attempt has been made to compile the results of experiments conducted on these aspects in past 10 years. We hope that low input sustainable technologies evolved by the concerted efforts of a multidisciplinary team of scientists involving disciplines of soil science, agronomy, pathology and microbiology for the management of resources like crop sequences, residues and scarce water would certainly be useful for long term sustainability in the region.

We express our sincere thanks and gratitude to Drs. A.S. Faroda and J. Venkateswarlu, Director and Ex-Director,CAZRI, Jodhpur, respectively for their constant encouragement. The help rendered by Dr.P.C. Bhatia, Assistant Director General, ICAR, New Delhi in giving valuable suggestions is duly acknowledged. The critical scientific comments and suggestions offered by the U.S. Cooperative Scientists Drs. James F. Parr, J.F. Power and R.I. Papendick during the course of investigations were quite constructive for which we feel indebted. Financial grant by USDA-FERRO, New Delhi, is duly acknowledged and for this we thank Mr. G.K. Gupta, Assistant Development Specialist, FERRO, New Delhi and Dr. James Stevenson of USDA, USA. We are grateful to Dr. A.V. Rao, Principal Scientist (Microbiology) of our institute for his contribution to microbiological aspects incorporated in this bulletin. Thanks are also due to staff of Integrated Nutrient Management, Plant Pathology and Agronomy Sections of the Division of Arable Cropping Systems for their help in various ways.

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Scenario of the Region

Indian arid region occupies nearly 12% of the country's geographical area (0.32 million km^2) of which 61% lies in 12 districts of west Rajasthan. The region is characterized by low precipitation (140 - 472 mm yr^{-1}), extremes of temperature (-2 to 48°C), high wind speed (35 to 40 km hr^{-1}) and high evapotranspiration. Approximately 95% of the rainfall is received in the monsoon (June-September) and the coefficient of variation ranges from 40 to 60%. Period of assured moisture supply varies from about 8 weeks in Jaisalmer to 15 weeks in Sikar district.

Soils of west Rajasthan are generally coarse textured with sand content varying from 90% in dunes to 60% in comparatively heavy textured soils. These are generally alkaline in nature with pH value varying from 7.4 in hilly soils to 9.0 in brown soils. Moisture retention capacity of arid soils ranges from 50 mm in dunes to as much as 200 mm $meter^{-1}$ in grey brown loam soils. Soils are prone to crusting after rains that impede seedling emergence and also accelerate runoff. A layer of concretes of $CaCO_3$ (hard pan) at varying depths is also found in part of the region. This strata has restricted permeability to infiltrating water as well as roots. Such soils are prevalent in Jodhpur (15%), Bikaner (7%) and Nagour (10%) districts. Sharma *et. al.*, (1966) and Mehta *et al.*, (1967) reported widespread deficiency of N in these soils but the contents of available phosphorus, potassium and micro-nutrients ranged from medium to adequate.

The irrigated area in arid region has increased from 0.79 Mha in seventies (Mann and Singh, 1975) to 1.62 Mha area in nineties (Anonymous, 1992). It is expected that 1.59 Mha area will be covered by Indira Gandhi Nahar Project (IGNP) and 1.1 Mha by wells and tubewells for irrigation by 2010 AD. But even then, ninety per cent of the area would remain rainfed. The situation in respect of irrigated agriculture is not very encouraging. Over exploitation of ground water has led to 3-7 meter fall in water table and development of salinity in soils (Singh, 1997). Simultaneously, indiscriminate use of water in high water requiring and long duration crops (groundnut, cotton, sugarcane) has caused waterlogging on 15000 ha covered under IGNP. It is estimated that this figure will increase to about 26500 ha in near future (Anonymous, 1997). Coupled with it, increasing human (47 persons per sq.km. in 1971 to 90 in 1991) and livestock (13 million in 1956 to 23 million in 1991) population are mounting pressure on dwindling land and water resources. Land holding has declined from 10.2 ha per capita in 1970 to 6.5 ha in 1990. These trends show the need to produce more from limited area and with restricted water supply in the region.

Crops are mostly grown in rainy season (July to October) and the cropping intensity is generally 100%. During the cropping period maximum temperature varies from 36 to 39^0 C with a diurnal variation of 10^{o}C, while soil temperature at 5 cm depth often reach 45^{o}C. Potential evapotranspiration (mm day^{-1}) during cropping period range from 0.3 to 5.6. Pearl millet (*Pennisetum glaucum* (L.) R.Br.) is the major cereal crop of the region. It is grown in 5 Mha under rainfed conditions, during July to October in rainy (*Kharif*) season and the productivity varies from 90 - 500 kg ha^{-1}. Pearl millet has shallow rooting habit like other cereals. Adaptation of pearl millet to water limiting environment has been thought to be due to its certain in-built opportunistic strategies, such as short duration of basic developmental stages, rapid post drought recovery, effective control of water loss and heat tolerance and not due to osmotic adjustments (Bidinger *et al.* 1981). However, where good quality ground water is available supplemental irrigation is given during the long spells of drought. Clusterbean (*Çyamopsis tetragonoloba* (L.) Taub.) grown in about 2 Mha rank next to pearl millet as an important rainfed crop. Traditionally this legume was grown for fodder and feed of the livestock only, however, in these years it has assumed a great importance mainly due to the presence of gum (galactomannan) in the endosperm which constitute about 30% of the whole seed. Gum has several diversified uses in textile, paper, food processing, chemicals, cosmetics, pharmaceutical, explosives and oil industries. Its average productivity is 239 kg ha^{-1}. Moth bean (*Vigna aconitifolia* Jacq. Marechal) and mung bean (*Vigna radiata* (L.) Wilczek.) are other important leguminous crops grown in 2 Mha with the average productivity of 220 kg ha^{-1}. In certain pockets where irrigation is available, wheat (*Triticum aestivum* L.), mustard (*Brassica juncea* L. Czern & Coss.) and cumin (*Cuminum cyminum* L.) are also grown during winter season (November- April).

The mean organic-C content in the arid soil ranges from 0.05% to 0.2% in coarse, 0.2-0.3% in medium and 0.3-0.4% in fine textured soils. This low organic-C is attributed to low clay content, hot climate and low rainfall (Dhir, 1977) and suggest low inherent fertility status. Among different nutrients, N is often most deficient (Sharma *et al.*, 1966) whereas the status of other nutrients ranges from medium to high (Mehta *et al.*, 1967).

Vegetation contain 5-10% of the total N found in the arid ecosystem as compared to 2% in grassland to nearly 15% in deciduous forest (Wallace *et al.*, 1978). Joshi (1993) reported low N contents in the arid soil of Rajasthan. N in soil persist mainly in organic forms, of which the acid hydrolyzable N fraction constitute about 62-87% of the total N (Aggarwal *et al.*, 1977, 1990). Content of different subfractions of hydrolyzable N decreases as amino acid-N > unidentified N > hydrolyzable NH_4-N > hexosamine-N (Praveen-Kumar and Aggarwal, 1997). Amino acid and hexosamine fractions often contribute more towards total hydrolyzable-N in the fine textured soils. Although absolute amount of hydrolyzable-N decreases with depth, but when expressed as per cent of total N, it generally follows an opposite trend. Vegetation also alters the distribution of organic N fractions (Praveen-Kumar and Aggarwal, 1997). Cultivation of legumes as annuals or trees increases the build up of hydrolyzable N fraction (Aggarwal and Praveen-Kumar, 1990, 1994; Aggarwal *et al.* 1993). Higher status of total N as well as hydrolyzable fractions was observed under the canopy of *Prosopis cineraria* (Praveen-Kumar and Burman, unpublished data). NH_4-N and NO_3-N are major inorganic forms and their concentration range from 10 - 15 and 2 - 5 $\mu g\ g^{-1}$ soil respectively. The level and distribution of NO_3-N in the soil profile is subjected to seasonal fluctuations. In Jodhpur soils the concentration of NO_3 in the upper layer of soil has been reported to increase from nearly 3 ppm in winter to more than 5 ppm in summer (Aggarwal and Praveen-Kumar, 1994). The fluctuations in NO_3-N concentration at lower depths were not conspicuous untill rainy season.

Rainfall and symbiotic N fixation are the natural sources for N addition in soil. Approximately 5.5 to 12.5 kg N is added in arid soil through rainfall every year (Aggarwal *et al.*, 1982; Vlek, 1981) whereas contribution of biological N fixers is about 3.6 Kg N $ha^{-1}yr^{-1}$ (Vlek, 1981).

Sequential cropping of traditional low yielding land races, poor fertility of soils and frequent occurrence of moisture stress at critical stage of crop growth are principal reasons of low productivity in the region. Farmers are cultivating pearl millet since ages and the farming system is mainly pearl millet based. However, repeated cultivation of pearl millet in the same piece of land has decreased its yield potential on one hand, while, increasing biotic pressure and urbanization, on the other, has compelled the growers to cultivate on low and marginal lands which were traditionally grassland and sand dunes. This has further decreased the yield levels, besides disturbing the ecosystem.

Under a good rainy season pearl millet withdraws 65 kg N to produce 1500 kg grain in a hectare. Of this, the contribution from soil organic matter, rainfall and biological N fixation may amount to 25 kg ha^{-1} (Praveen-Kumar and Aggarwal, 1997). Therefore, to achieve a good yield, N needs to be supplemented from other sources to make up the remaining 40 kg N ha^{-1}. But, due to uncertainity of rainfall events at critical stages of crop growth under rainfed conditions, use of fertilizer N increases risk factor in monetary terms. Further, losses of applied N as ammonia are also very high leading to low utilization efficiency by the crop (Aggarwal *et al.*, 1987). On the contrary, responses to N are high under good rainfall or well irrigated conditions. Since water is a scarce resource in the region, N use need to be adjusted depending on the situations of water availability.

N application under all these situations improve the yield but its utilization efficiency is very low on marginal lands and under continuous pearl millet cultivation. This trend can only be reversed by adopting cropping systems involving the leguminous crops like clusterbean, moth bean and mung bean which can restore soil fertility. Since application of N in high quantities is not possible due to associated risks, returning a part of what has been extracted from soil as crop residue can be another alternative for restoring nutrients and improving organic base.

Short and long durations of moisture stress under rainfed conditions also favor occurrence of charcoal or dry root rot caused by *Macrophomina phaseolina* (Tassi) Goid - a serious disease of many legumes and oilseed crops grown under arid and semi-arid conditions (Lodha *et al.*, 1986). Disease intensity is directly proportional to the inoculum density of this fungus in soil (Cook *et al.*, 1973). In order to minimize the severity of the disease it is essential to reduce the inoculum density in the soil by crop management practices. Incorporation of organic amendments and crop residues in the soil is one such approach through which population densities of soil borne pathogens can be minimized (Ghaffar *et al.*, 1969). Experiments were concurrently initiated to study effect of crop residues in conjunction with or without fertilizer-N on population dynamics of *M. phaseolina*.

Therefore, an integrated approach involving fertilizer-N, crop residues, on farm waste of animal origin, legume based cropping systems, optimum tillage and judicious utilization of scarce water resources is the only option for enhancing crop productivity. The present study, encompasses our efforts on these approaches for increasing soil productivity and crop yield on a sustainable basis.

Experimental Site

Location

All the experiments presented in this compilation were carried out at the Central Arid Zone Research Institute, Jodhpur (India) situated at $26^{0}18'$ N and $73^{0}01'$ S. The city of Jodhpur is considered as Gate way of the Great Indian Thar desert. With an average annual rainfall of 360 mm yr^{-1} it is the most important and largest city of western Rajasthan.

Soils

Soil of the experimental area was **Typic Camborthid** with loamy sand texture (sand 85.1%, silt 9.9% and clay 4.5%). It had 1.56 g cm^{-3} bulk density, 8.1 pH (soil:water 1:2.5), 0.2 dS m^{-1} EC (soil:water 1:2.5), 1.9 g kg^{-1} soil organic-C, 300 mg kg^{-1} total N, 270 mg kg^{-1} total P, 7.0 mg kg^{-1} available-P. This light textured soil is a typical representative of more than 60% of the cultivable area of the region.

Rainfall

The rainfall ranged from 182.0 to 421.5 mm during the cropping periods (1990-1996). 247.3 mm rainfall was received during crop growth period in 1990. Exceptionally high rainfall (516 mm) was received between July 3 - 7, 1990 before sowing of the crop. Distribution of rainfall from sowing till harvest for each year (1991 - 1996) has been illustrated in figure 1.

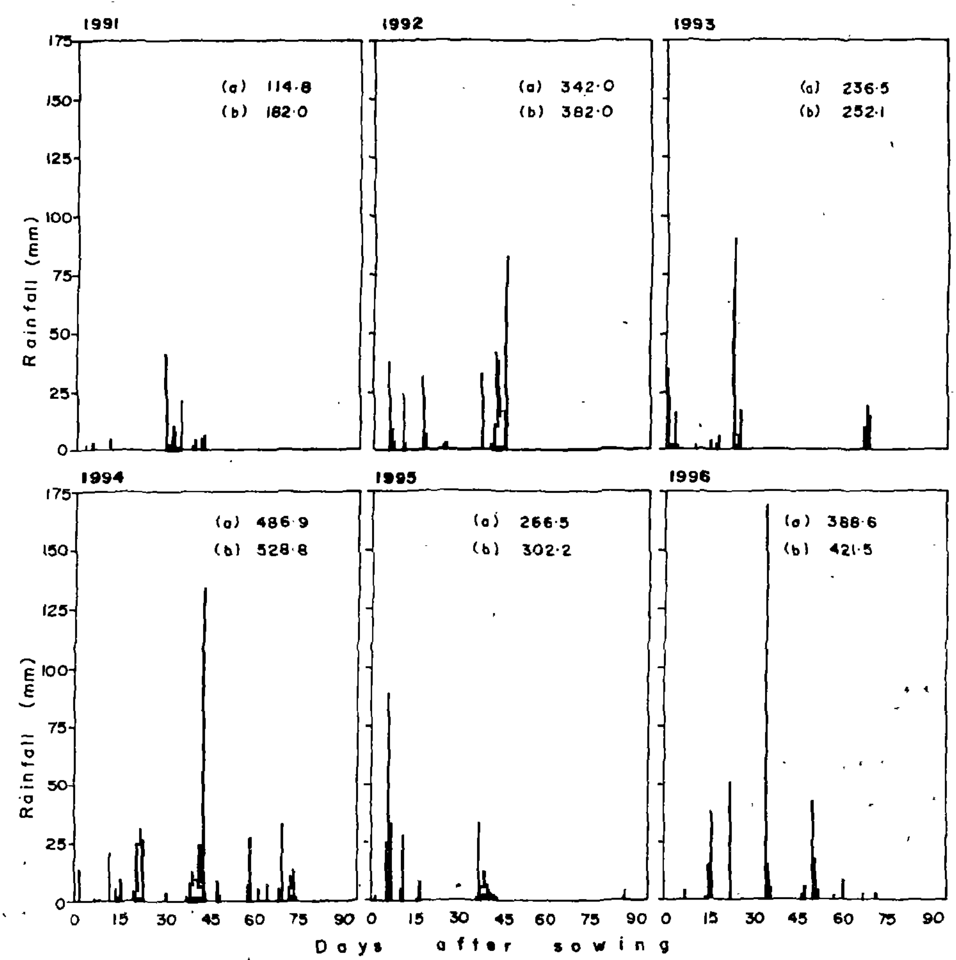

Figure 1. Distribution of rainfall in cropping period from 1991 to 1996; (a) sowing to harvest of the crops and (b) cropping season (June to October).

Use of Crop Sequences

The productivity of pearl millet, is generally higher when grown in rotation with legumes as compared to its continuous monoculture. Mann and Singh (1977) found 62% yield reduction in monoculture of pearl millet as compared to pearl millet grown in cropping sequence with clusterbean. Singh *et al* ., (1985) recorded 11% higher pearl millet yield in pearl millet-clusterbean cropping sequence than its continuous cultivation. The decline in pearl millet yield in continuous monoculture is attributed to depletion of nutrients, production of some allelo-chemicals (Narwal, 1989; Saxena *et al.*, 1995) and increase in disease incidence while the beneficial effect of legumes is attributed to improvement of soil fertility (Oswal *et al.*, 1989) and health.

Another reason for including legumes in cropping systems is that delayed onset of monsoon is a common feature of the region. Pearl millet yields are very low under late sown conditions whereas legumes yields very well even under these conditions. It is also an established fact that under rainfed conditions crop rotation strategies prevent the build up of soil borne pathogens and development of new races. Cultivation of pearl millet in fallow based cropping system has also been found more remunerative than monoculture (Singh, 1980).

Informations on quantitative and qualitative changes in soil fertility and productivity as influenced by cropping sequences involving pearl millet as a base crop are required for sustainability of productivity in the region. In this section attempts are made to study the influence of different cropping sequences on changes in soil fertility parameters and pearl millet yield.

Experimental Procedures

The experiment was conducted from 1990 to 1994. Eight cropping sequences involving pearl millet and two legumes viz. clusterbean (CB) and mung bean (MB) were established. Keeping of the land fallow (F) for a year after pearl millet cultivation was also adopted as a cropping sequence. Only one crop was grown each year. The sequences of cultivation of different crops were (1) PM-PM-PM-PM-PM, (2) F-PM-F-PM-PM, (3) MB-PM-MB-PM-PM (4) F-MB-MB-PM-PM, (5) MB-MB-MB-PM-PM, (6) CB-PM-CB-PM-PM, (7) F-CB-CB-PM-PM and (8) CB-CB-CB-PM-PM. These are designated as CS_{1-8} in the text, tables and figures to follow. Only pearl millet was fertilized with three levels of N (20, 40 and 60 kg N ha^{-1}).. After the harvest of the crops at maturity, grain and straw yields were recorded. All crops were grown as rainfed in all the years.

Nitrogen content of grain and straw was estimated (Bremner, 1965a) and the N use efficiency from the data was calculated by the difference method :

$$NUE = 100 \times (f-c)/a$$

where 'f' and 'c' are total uptake of N (kg ha^{-1}) from fertilized and control plots, respectively and 'a' being rate of N application (kg ha^{-1}).

Soil samples were collected after harvest in 1992 and in 1994 at 0-15 and 15-30 cm depths with a soil auger. Organic-C (Jackson, 1967), total-N (Bremner, 1965a), organic forms of N (Bremner, 1965c), available-P (Olsen and Dean, 1965), available micro-nutrients (Lindsay and Norvell, 1978), phosphatases (Tabatabai and Bremner, 1969), and dehydrogenase (Tabatabai, 1982) were estimated in soil samples. NO_3-N from soil was extracted with 2 M KCl (Bremner, 1965b) and was estimated by using flow-injection analyzer (Tecator). Population of nitrifying bacteria was estimated by MPN method (Alexander and Clark, 1965). Data of soil analysis were expressed on oven-dry basis.

Accomplishments

Chemical and Biochemical Properties of Soil

Changes in biochemical properties were estimated at two stages i.e. after establishment of cropping sequences in 1992 and at the end of the study in 1994.

(a) After Establishment of Crop Sequences (1992)

Cropping sequences that contained legume (CB or MB), in general, had more organic-C than those without any legume. Maximum organic-C was observed after three year continuous cultivation of CB (CS_8) (Table 1). Comparison of organic-C in CS_4 with CS_7 and CS_5 with CS_8 indicated it to be higher in CB based cropping sequences. Organic-C content decreased with depth and significant differences were not observed between all the cropping sequences and initial level, excepting in CS_5 and CS_8 where it was significantly higher.

Changes in the status of the total-N, available-P and NO_3-N (Table 1 and 2) with different cropping sequences largely followed the trends presented for organic-C at both the soil depths. Most cropping sequences except CS_5 and CS_8 did not significantly influence the status of any micro-nutrient in soil. Status of Fe and Zn was significantly higher in CS_7 while that of all the four available micro-nutrients was higher under CS_8 as compared to the initial level (Table 1).

Table 1. Changes in organic-C, Olsen-P, NO_3-N and micro-nutrients content in soil after three years cropping sequences.

Cropping System	Organic-C (%)		Olsen-P (μgg^{-1})		NO_3-N (μgg^{-1})		Fe (μgg^{-1})	Zn (μgg^{-1})	Cu (μgg^{-1})	Mn (μgg^{-1})
	Depth (cm)									
	0-15	15-30	0-15	15-30	0-15	15-30	0-15	0-15	0-15	0-15
Initial	0.22	0.14	6.14	5.54	2.02	1.45	1.96	0.32	0.16	5.31
CS_1	0.22	0.14	6.20	5.57	2.26	1.32	1.98	0.31	0.15	5.29
CS_2	0.21	0.15	6.06	4.96	2.12	1.20	1.98	0.32	0.14	5.30
CS_3	0.23	0.15	7.75	5.39	2.46	1.55	2.01	0.35	0.16	5.28
CS_4	0.24	0.15	7.98	4.58	2.85	1.62	2.04	0.35	0.15	5.30
CS_5	0.26	0.19	8.28	4.34	3.43	2.04	2.07	0.39	0.17	5.35
CS_6	0.22	0.15	7.29	4.80	2.39	1.44	2.04	0.33	0.16	5.31
CS_7	0.26	0.16	7.86	4.53	3.77	1.63	2.08	0.37	0.16	5.37
CS_8	0.28	0.17	9.22	4.37	4.27	3.36	2.12	0.41	0.20	5.41
LSD (p=0.05)	0.01	0.01	0.57	0.59	0.07	0.06	0.09	0.06	0.03	0.11

Lowest content of the hydrolyzable NH_4-N, hexosamine-N and amino acid-N was found in CS_1 (Table 2). Incorporation of legumes or practicing of fallow in cropping sequences increased these fractions as well as their contribution towards total-N pool. In CS_1, hydrolyzable NH_4-N, hexosamine-N, amino acid-N and total hydrolyzable-N in CS_2 accounted for 10.82, 6.78, 35.42 and 66.02% of total-N, respectively as against 11.76, 7.90, 38.46 and 70.04%, respectively for CS_2. Contribution of unidentified-N forms and non-hydrolyzable-N decreased from 12.98 and 33.97% of total N in CS_1 to 11.80 and 29.95% for CS_2 even while concentration of total N remained unchanged. Comparison of different organic fractions in continuous PM cultivation (CS_1) with any of the legume based cropping sequence revealed similar trend. In comparison to initial concentration of different fractions, cultivation of both the legumes increased the concentrations of hydrolyzable NH_4-N, hexosamine-N and amino acid-N but decreased those of non hydrolyzable-N and unidentified-N (Fig. 2). This effect became more pronounced with increased numbers of years of legume cultivation. Among any two comparable CB and MB based cropping sequences, magnitude of these changes in the different fractions after CB was often more than that recorded after MB cultivation. The opposite trend was observed for continuous PM cultivation.

Table 2. Effect of different cropping sequences on the distribution of different organic fractions ($\mu g\ g^{-1}$) of soil N in 0-15 cm soil depth.

Cropping sequence	Hydrolyzable-N					Nonhydro-lyzable-N	Total-N
	Hydrolyzable NH_4	Hexosamine	Amino acid	Unidentified	Total		
CS_1	31.59	19.80	103.34	37.88	192.62	99.12	291.74
CS_2	34.32	23.05	112.45	34.43	204.25	87.36	291.62
CS_3	32.79	19.47	116.12	36.18	204.57	86.22	290.80
CS_4	42.65	21.92	117.03	28.99	210.61	83.22	293.84
CS_5	46.22	31.85	30.79	21.19	230.00	65.44	295.52
CS_6	42.14	19.83	121.84	28.54	212.36	87.46	299.82
CS_7	44.47	29.50	162.75	11.76	248.49	57.26	305.76
CS_8	46.17	36.46	165.04	11.59	259.27	46.74	306.02
LSD ($p= 0.05$)	2.63	3.57	5.66	1.00	7.76	6.36	9.61

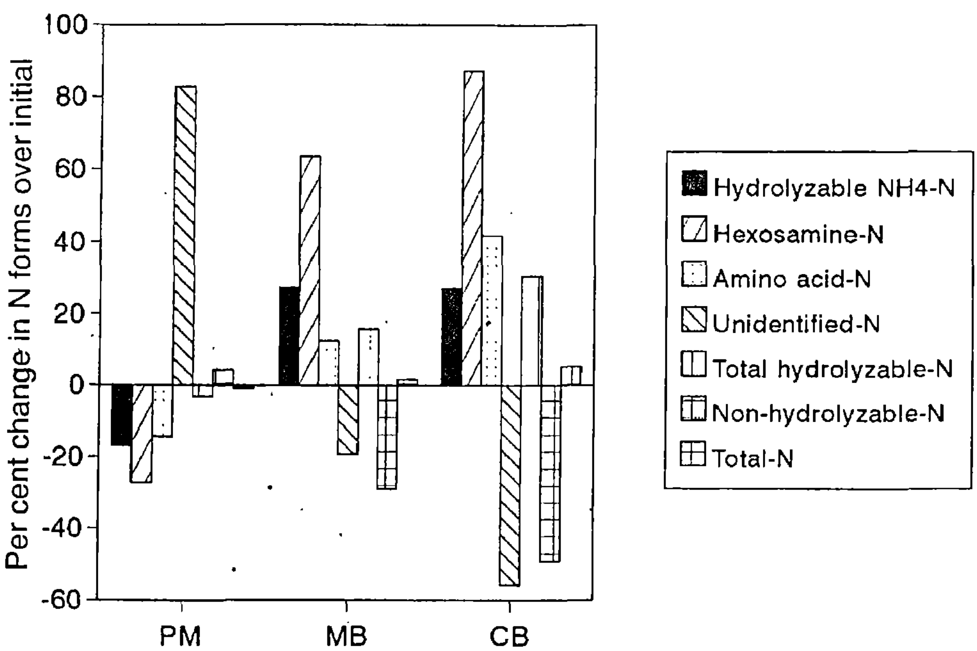

Figure 2. Effect of continuous cultivation of pearl millet (PM), mung bean (MB) and clusterbean (CB) on changes in organic fractions of N in the soil.

Activities of acid and alkaline phosphatases and dehydogenase were minimum in the CS_2 followed by CS_1 (Table 3). Between the two comparable legume based cropping sequences, activities of acid and alkaline phosphatase in surface soil were higher in CB than the MB based cropping sequences while the opposite was true for dehydrogenase. However, under both the legume based cropping sequences enzyme activities increased with number of years of their cultivation. Activities of enzymes in sub-surface soil (15-30 cm) of all cropping sequences were lower than surface soil (0-15 cm) and the effect of cropping sequences was not significant.

(b) At the End of Experiment (1994)

Status of organic-C in 1994 in most cropping sequences was lower than that recorded in 1992. This decline was maximum in CS_5, CS_7 and CS_8. Similar trend was observed for total-N, available-P, micro-nutrients, etc. Remarkable increase in hydrolyzable NH_4-N, amino acid-N and hexosamine-N fractions observed in legume based cropping sequences also diminished after pearl millet cultivation for two successive years (Fig. 3). Concentration of these fractions in legume based cropping systems in 1994 was similar to initial level. Activities of enzymes like dehydrogenase, acid and alkaline phosphatase also decreased in all the cropping sequences as compared to that in 1992. But the trend remained similar to that observed in 1992 though variations between cropping sequences were very small.

Table 3. Changes in enzyme status at two different soil depths after three years under different cropping sequences.

Crop Sequence	Acid phosphatase (n kat 100 g^{-1} dry soil)		Alkaline phosphatase (n Kat 100 g^{-1} dry soil)		Dehydrogenase (p Kat g^{-1} dry soil)		Nitrifying bacteria (x 10^4 g^{-1} dry soil)	
	Depth (cm)							
	0-15	15.30	0-15	15-30	0-15	15-30	0-15	15-30
Initial	2.98	1.95	8.23	3.84	9.85	7.68	0.68	0.28
CS_1	3.20	2.08	8.99	4.81	10.16	8.09	0.75	0.28
CS_2	2.42	1.71	6.75	4.18	9.31	6.49	0.64	0.27
CS_3	3.18	2.25	9.02	4.96	10.63	7.96	0.93	0.34
CS_4	3.80	2.36	9.41	4.96	11.72	8.19	0.98	0.31
CS_5	3.85	2.74	9.63	5.49	13.17	8.52	1.17	0.38
CS_6	3.63	2.23	9.71	4.78	10.26	7.47	0.97	0.41
CS_7	3.97	2.49	9.54	5.21	11.10	8.22	1.08	0.31
CS_8	4.25	3.00	11.64	5.57	12.60	8.31	1.37	0.43
LSD (p=0.05)	0.16	0.20	0.36	0.43	0.45	0.16	0.18	0.11

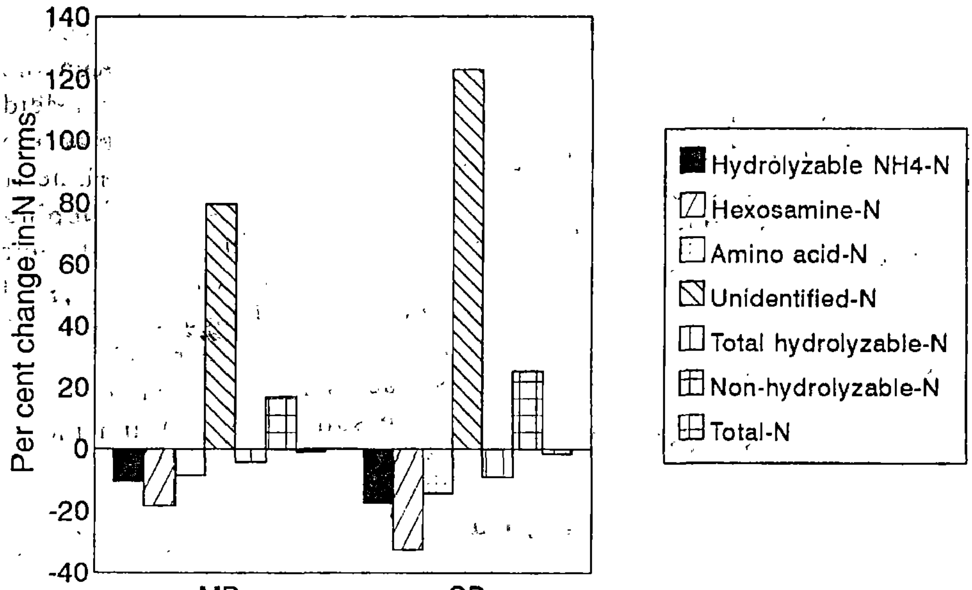

Figure 3. Changes in organic fraction of N after two years of pearl millet (PM) in plots with three years of clusterbean (CB) and mung bean (MB) cultivation.

Grain and Straw Yield

(a) After Establishment of Crop Sequences (1993)

The grain yield of the pearl millet grown under different cropping sequences varied significantly (Table 4). In general lowest yields were recorded in CS_1. Yield in CS_2 was slightly higher than in CS_1. Inclusion of both the legumes in the cropping sequence (CS_3 - CS_8) increased PM yield as compared to CS_1. Comparison of the yield levels in the CS_3 with CS_6, CS_4 with CS_7 and CS_5 with CS_8 indicated that the grain yield was higher in the plots where CB was grown as compared to those with MB. Further analyses of data revealed that the PM grain yield (without N) was nearly 29, 44 and 65% higher in the three MB based cropping sequences i.e. CS_3, CS_4 and CS_5, respectively in comparison to CS_1. Similarly the grain yield in the three CB based cropping sequences i.e. CS_6, CS_7 and CS_8 was nearly 50, 85 and 100% higher.

Pearl millet responded favorably to N application upto 40 kg N ha^{-1} in all the cropping sequences. Further increase in the rate of N application to 60 kg ha^{-1} showed no significant effect over 40 kg N application in CS_1 - CS_6. But under CS_7 and CS_8 pearl millet yield significantly increased upto 60 kg N ha^{-1}. At any level of N, yield under CB based cropping sequences was higher than comparable MB based cropping sequences. At 40 kg N level yield under different cropping sequences increased in the order $CS_1 < CS_2 < CS_3 < CS_4 < CS_6 < CS_5 < CS_7 < CS_8$. Similar trend was also observed at two other levels of N. Interestingly pearl millet yield at any level of N application under cropping sequence CS_1 was nearly 50% than that recorded in cropping sequence CS_8 at respective level of N application.

(b) At the End of Experiment (1994)

The trends in pearl millet yield under different cropping sequences were similar to those reported for first year (Table 4). The results suggest that beneficial effect of legumes on pearl millet also persisted for second year. Per cent increase in grain yield over CS_1 (continuous PM cultivation, without N) was maximum in CS_8 (64.0%). The corresponding value in 1993 was 100.0 (Fig.4). Similar trend was also observed for other cropping sequences.

Table 4. Grain yield of pearl millet under different cropping sequences in 1993 and 1994.

1990	PM	F	MB	F	MB	CB	F	CB
1991	PM	PM	PM	MB	MB	PM	CB	CB
1992	PM	F	MB	MB	MB	CB	CB	CB
1993	**PM**	**PM**	**PM**	**PM**	**PM**	**PM**	**PM**	**PM**
Control	3.4	3.8	4.4	4.9	5.6	5.1	6.3	6.8
N 20	4.8	5.3	5.6	5.9	6.3	6.4	7.6	8.5
N 40	4.9	5.6	6.0	6.2	7.1	7.0	8.5	9.3
N 60	4.9	5.5	6.0	6.5	7.1	7.1	9.2	10.3
LSD(p=0.05) N level 0.3, Cropping sequence 0.7, N X Cropping System 0.8								
1994	**PM**	**PM**	**PM**	**PM**	**PM**	**PM**	**PM**	**PM**
Control	5.0	5.2	5.5	6.2	7.1	6.2	7.4	8.2
N 20	7.9	9.6	10.1	10.4	11.1	10.8	11.9	12.1
N 40	10.2	11.9	12.5	13.4	14.1	13.9	14.7	15.4
N 60	10.9	12.5	13.0	14.1	14.9	14.7	15.8	16.5
LSD(p=0.05) N level 0.9, Cropping sequence 1.2, N X Cropping System 2.3								

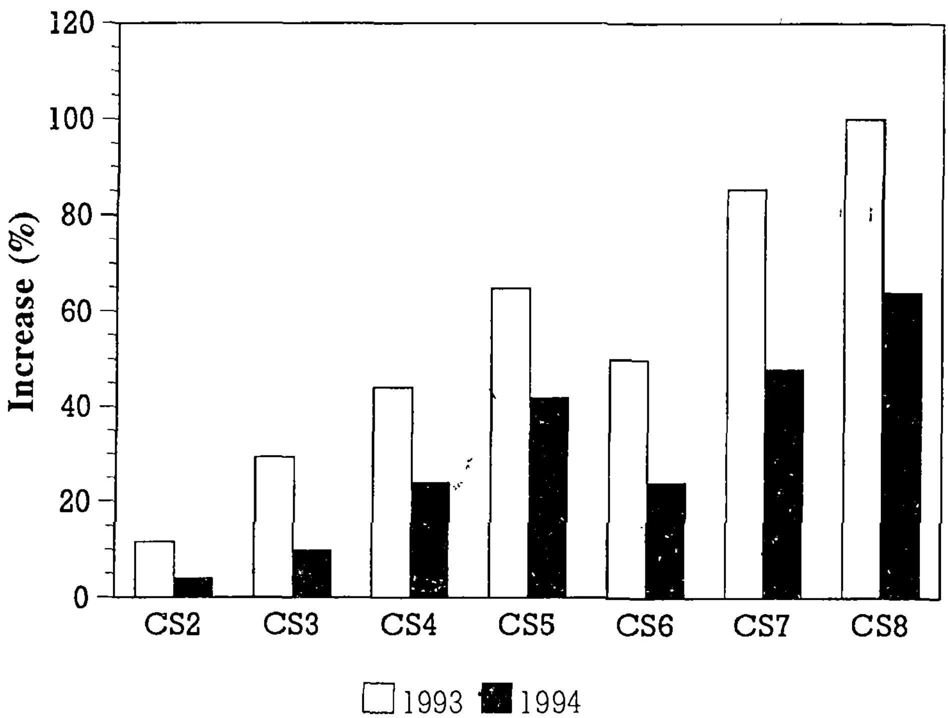

Figure 4. Per cent increase in grain yield of pearl millet (PM) in different cropping sequences in comparison to CS-continuous pearl millet cultivation. (CS_2 F-PM-F-PM-PM; CS_3 MB-PM-MB-PM-PM; CS_4 F-MB-MB-PM-PM; CS_5 MB-MB-MB-PM-PM; CS6 CB-PM-CB-PM-PM; CS_7 F-CB-CB-PM-PM; CS_8 CB-CB-CB-PM-PM; PM - Pearl millet, MB - Mung bean; and CB-Clusterbean and F-fallow)

Nitrogen Use Efficiency Of Pearl Millet

(a) Cropping Season (1993)

N use efficiency (NUE) varied 12-50% under all the cropping sequences but decreased with the increasing levels of fertilizer N (Fig.5). The NUE was lowest under continuous cultivation of PM, being 25.53, 14.08 and 10.31% at the N application rates of 20, 40 and 60 kg ha^{-1}, respectively. The NUE was higher under fallow or legume based cropping sequences with maximum being in CS_8.

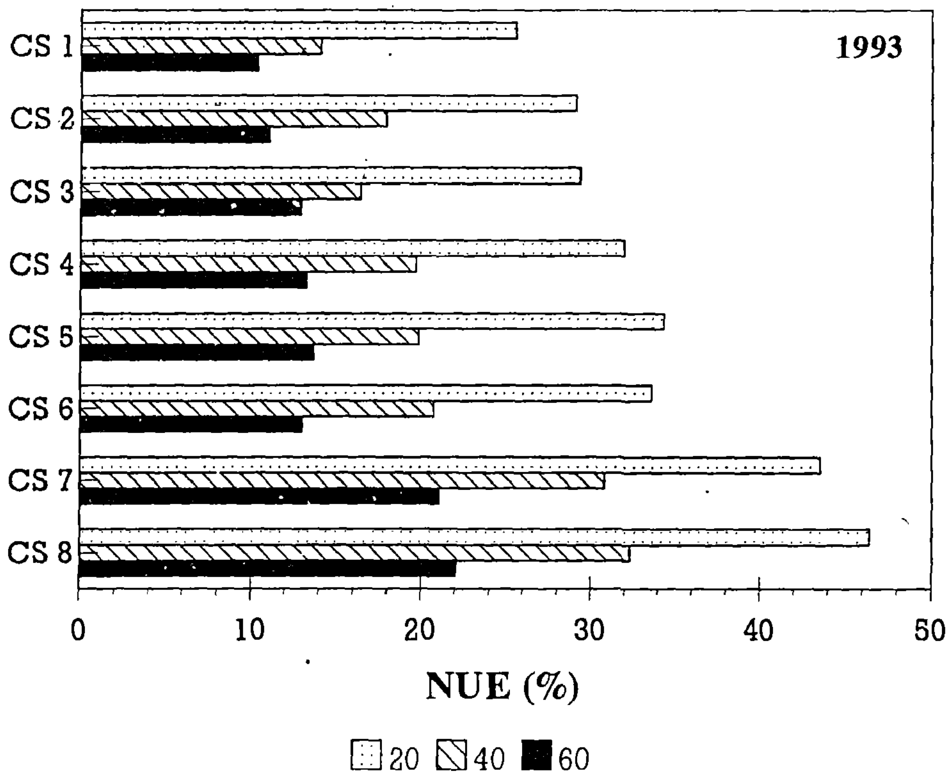

Figure 5. Nitrogen use efficiency (NUE) of pearl millet under different cropping sequences (see figure 4 for cropping sequences) at 20, 40, 40 and 60 kg N ha^{-1} in 1993.

(b) Cropping Season (1994)

N use efficiency ranged between 30 to 60% under all the cropping sequences and was generally minimum in CS_1 at all the levels of application (Fig. 6). It was 46% in CS_1 which increased to 55% in CS_2 for 20 kg N ha^{-1} but in remaining cropping sequences it varied marginally between 55-59 %. A range of 45-59 and 31-60% in NUE was recorded for 40 and 60 kg N, respectively. Interestingly, values of NUE were maximum and very close to each other (around 59%) at all the levels of N application in CS_8. Such a situation was not observed in preceding year (1993).

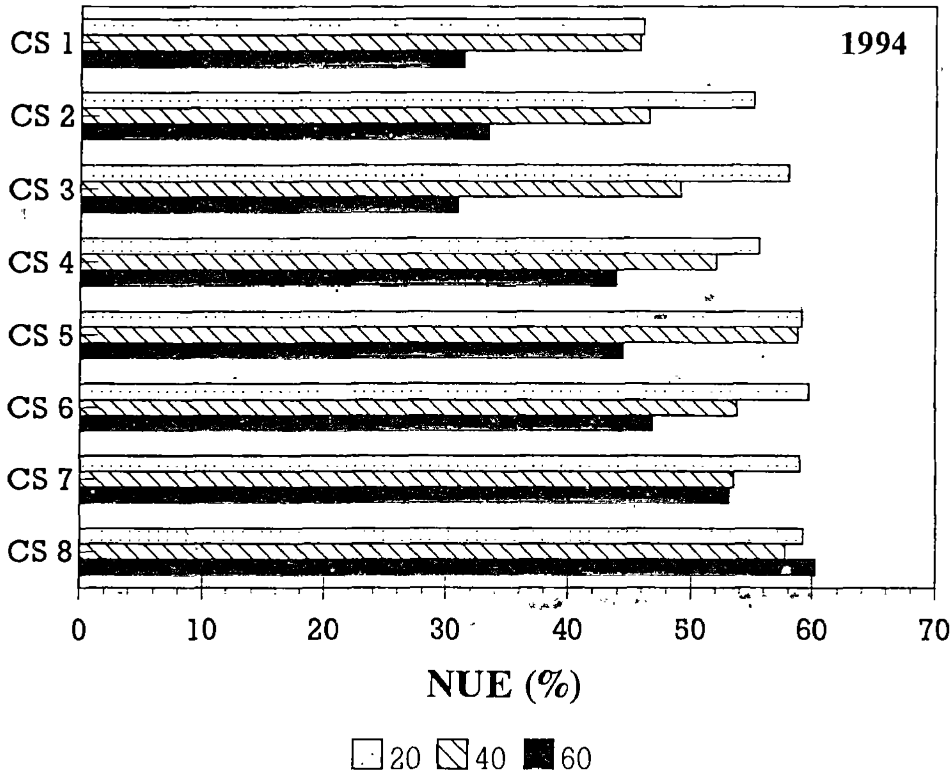

Figure 5. Nitrogen use efficiency (NUE) of pearl millet under different cropping sequences (see figure 4 for cropping sequences) at 20, 40, 40 and 60 kg N ha^{-1} in 1994.

Discussion

Variations in the organic-C content among different cropping sequences may be attributed to the amount of root residue left in the soil, quantity of leaf fall and their decomposition (Vyas and Desai, 1953; Nnadi and Balasubramanian, 1978; Odell *et al.*, 1984). Higher organic-C in the surface soil under CB may be due to higher leaf fall and its lower C:N ratio as compared to MB and PM based cropping sequences (Praveen-Kumar and Aggarwal, 1997). As a result, microbial activity under CB based cropping sequences was also higher (Table 3) leading to higher organic-C (Table 1). Increase in soil organic-C following pigeonpea based cropping sequences (Rego, 1992) and addition of crop residues (Doran and Smith, 1987) have also been reported. Since the quantity of root and leaf residues reaching in 15-30 cm soil depth was small, the differences among cropping sequences were also not significant at this depth.

Higher total-N in legume based cropping sequences may be assigned to its fixation, and also to addition of leaf litter to soil. Increased quantity of total-N in CB than MB based cropping sequences may be due to higher N fixation in addition to more leaf litter fall in soil as CB has an inherent capacity to shed its leaves under moisture stress, a common feature at crop maturity. Higher NO_3-N in the legume based cropping sequences has also been observed by Oswal *et al.*, (1989) and Rego (1993) and may be attributed to the mineralization of a part of N fixed. Differences in organic fraction of N under some cropping sequences even when total N remained unchanged were surprising and indicate a strong crop effect. Crops are known to differ in the type of root exudates and dominant microflora in rhizosphere (Nye and Tinker, 1977). Further, mineralization of their residues may also effect the microbial activity. These factors individually or in association may influence the content of amino acid and hexosamine N which are known to be of microbial origin (Parsons and Tinsley, 1975). Microbial activity under legume based cropping sequences was generally higher than in pearl millet based cropping sequences (Table 3) which may explain higher status of amino acid-N and hexosamine-N under these cropping sequences. The increase in amino acid-N, hexosamine-N could not be accounted by the changes in total-N, therefore it was evident that these changes were due to redistribution of N among different fractions rather than N fixation.

Variations in the availability of phosphorus and micro-nutrients under different cropping sequences also indicate a strong crop effect. Their availability is influenced by a crop through a variety of physical, chemical and biological effects (Nye and Tinker, 1977). In the present experiment no attempt was made to quantify such effects but highest microbial activity was observed under MB followed by CB and PM based cropping sequence while the C:N ratio of residues was maximum for PM and minimum for CB. Higher production of organic acids from decomposing residues was thus obvious under CB based cropping sequences and may explain higher availability of P and micro-nutrients.

Evaluation of the effect of cropping sequences in terms of N required to produce equivalent grain yield was not possible in our experiment as the grain yield in some cropping sequences was much higher than obtained with any level of fertilizer N. Reasons for the same are not clear. Brawand and Hossner (1976), Classen and Kissel (1984) and Clegg (1982) have reported that response of corn to crop rotation was more in stress years than in favorable ones. As 1993 was a stress year for pearl millet production, therefore, the same reasons as advanced for corn may explain our observations.

Lowest crop yields in our experiment were observed where PM was grown continuously i.e CS_1. Mann and Singh (1977), Singh (1980) and Singh *et al.*, (1985) have also reported decline in PM yield following its continuous cultivation. Narwal (1989) and Saxena *et al.*, (1995) attributed this decline in yield to autotoxicity of pearl millet. Comparatively higher yield in CS_2 than CS_1 may either be due to leaching or decomposition of toxic substances during the fallow period. Higher PM yield under legume based cropping sequence can be due to (i) fixation of N (ii) associated improvement in biological properties of soil and (iii) alleviation of the adverse effect of toxic substances. Effect of legumes on these parameters increased with years of their cultivation which explain the similar trend observed for yield.

The finding of our study demonstrated that high production levels of pearl millet can be achieved with or without fertilizers by adopting a cropping sequence including legumes particularly clusterbean.

Use of Crop Residues

For Improving Soil Fertility and Pearl Millet Yield

Crop residues management assumes importance in rainfed cropping system of arid region where due to soil degradation, low soil organic-C and moisture stresses, yield levels are very low and variable from zero to three times of long term average yield (Tucker, 1988). Use of fertilizer-N to increase the production level is risky under the situations of low and erratic rainfall. Apart from risk, fertilizers also pollute environment due to high volatilization losses (Aggarwal *et al.*, 1987). Crop residues are an important source of nutrients and also improve the physical and biological properties of soils (Venkateswarlu and Hegde, 1992). It is estimated that about 236 Mt straw/stover are produced in India from five major cereal crops and even if 50 per cent of these residues are used as animal feed, the rest can be recycled in soil (Gaur, 1992). Decomposition and release of nitrogen from residues depends on the soil climatic conditions and C:N ratio of plant residues (Prasad and Power, 1991). Crop residues vary widely in C:N ratio, with higher values from cereals and generally lower values from legumes. However, considering the slow decomposition of residues in arid environment, whole of the crop N requirement cannot be met only from this source. Therefore, an integrated nutrients supply from inorganic sources and crop residues will be more compatible approach under the arid conditions.

In this study, effects of crop residues of pearl millet (PM), clusterbean (CB) and mung bean (MB) were evaluated in comparison to farmyard manure (FYM) and fertilizer-N on the yield of pearl millet and soil quality under rainfed growing conditions.

Experimental Procedures

The experiment was conducted from 1991 to 1994 in a split-plot design with the different types of residue and FYM in the main plots. Farmyard manure and all the residues were separately incorporated in soil each year in October beginning from 1990 (Table 5). The field was kept fallow till the next sowing. The residues of CB and MB contained both stalk and the leaves and their respective quantity was decided by the amount of leaf fall under natural conditions. The residues of CB and MB or FYM were incorporated equivalent to 20 kg N ha^{-1} whereas; PM residues contributed about 7.2 kg N ha^{-1}. Amount of PM residues equivalent to 20 kg N ha^{-1} was not incorporated as these are largely used as animal feed in this region. Pearl millet (cv. MH 179) was sown on 22nd July, 25th July, 28th June and 3rd July in 1991, 1992, 1993 and 1994, respectively after receiving sufficient rainfall. The crop had to be resown in some of the furrows on August 1, 1992 and in whole of the experiment on July 12, 1993, due to poor germination. Three levels of N viz., 0, 20 and 40 kg ha^{-1} were then applied in three splits. Crop was harvested at maturity and the yield data were recorded. The N content of grain and straw was estimated and the N use efficiency from the data was calculated by method described in previous section. Changes in organic-C, total-N, available-P, and the activity of dehydrogenase and phosphatase were also estimated by the methods described in previous section. Available-N and biomass-C were estimated by the methods of Subbiah and Asija (1956) and Jenkinson and Powlson (1976), respectively.

Table 5. Nitrogen content and the amount of different crop residues and farmyard manure added in field (average of four years).

Crop residue	Amount added kg ha^{-1}	N %	N added kg ha^{-1}	C:N
Clusterbean				
Leaf	800	1.46	11.7	22:1
Stalk	867	0.96	8.3	52:1
Mung bean				
Leaf	453	1.35	6.1	27:1
Stalk	2266	0.61	13.9	60:1
Pearl millet	1411	0.51	7.2	80:1
Goat manure	2000	1.00	20.0	29:1

Accomplishments

Grain and Straw Yield

Pearl millet crop experienced moisture stress throughout the growing season in 1991 as a result grain yields were low. In 1992, crop experienced moisture stress at flowering to grain development stage that adversely affected yield even though total rainfall was higher and its distribution was relatively better than 1991. Crop that was resown in 1992 experienced even higher water scarcity due to failure of monsoon later. Next year i.e. 1993, crop emergence was poor and stand was uneven initially and the resowing was also not successful, because of heavy rains soon after sowing and drought at later stages. Good grain yield was, however, obtained in 1994 due to evenly distributed rainfall. Treatment effects were discernible in all the years (Table 6). Maximum grain yield (without N) in 1991 was recorded in plots amended with CB residue, but in 1992 and in 1994 plots amended with FYM produced highest grain yield. Among residues, grain yield with CB residue was higher than that obtained with any other residue in all the years. Addition of MB and PM residues did not show any significant effect compared to control.

In 1991, the addition of fertilizer N alone significantly increased grain yield over control. However, the difference in grain yields obtained with 20 and 40 kg fertilizer N was not significant. Grain yield obtained with 20 kg fertilizer N alone was similar to that obtained with the addition of CB residue or FYM alone. Similar trend was observed in 1992. But in 1994, grain yield in plots amended with FYM was higher however, in those amended with CB residue was lower than that obtained with 20 kg fertilizer N alone. Grain yield with 40 kg N was also significanly higher than that obtained with 20 kg fertilizer N this year.

Application of 20 kg fertilizer N ha^{-1} in conjunction with clusterbean residues significantly increased pearl millet grain yield as compared to that of fertilizer N alone but not against the application of clusterbean residue alone in 1991. Grain yield with conjunctive application of 20 kg fertilizer N with other crop residues or FYM was higher than their application alone but the differences were not significant. Conjunctive application of 40 kg fertilizer N with clusterbean residues or FYM, however, produced significantly higher yield than their application alone. Similar trends were observed in 1992 and 1994. Variation in straw yield in all the years followed the trends similar to those presented for grain yield of respective years (Table 6).

Table 6. Effect of crop residues, farmyard manure (FYM) and fertilizer N on grain and straw yield of pearl millet (q ha^{-1}).

N levels	Grain yield					Straw Yield				
(kg ha^{-1})	Control	CBR	PMR	MBR	FYM	Control	CBR	PMR	MBR	FYM
1991										
0	3.1	5.5	4.5	4.6	5.2	7.6	13.3	10.8	11.3	13.7
20	5.0	6.1	5.1	5.5	6.0	11.6	14.7	11.2	13.4	15.6
40	5.5	7.4	5.7	6.5	8.0	12.5	16.0	12.3	15.6	18.4
LSD (p = 0.05)	N levels 1.1		Residues 1.6			N levels 3.2		Residues 2.1		
1992										
0	3.6	4.8	4.1	4.1	5.4	8.1	12.2	9.6	10.7	14.3
20	5.1	6.4	5.7	5.4	6.7	11.3	15.0	12.4	16.8	16.8
40	5.5	6.9	6.0	6.6	7.4	13.4	18.4	14.3	17.2	19.3
LSD (p = 0.05)	N levels 1.5		Residues 1.8			N levels 2.5		Residues 2.3		
1994										
0	5.9	8.1	5.3	5.6	12.6	13.1	18.1	15.6	14.8	23.9
20	10.7	15.2	10.0	9.9	6.6	20.9	25.8	29.7	21.6	28.4
40	14.3	18.3	15.3	14.1	20.8	25.3	34.3	30.8	27.9	36.9
LSD (p = 0.05)	N levels 1.7		Residues 2.1			N levels 3.8		Residues 4.7		

N-Use Efficiency

Nitrogen use efficiency (NUE) of 20 kg fertilizer N was 33.0% in control during 1991 which increased to 52.1 and 49.9% with the addition of CB residues and FYM. The comparable figures for the same level of N were 27.1, 62.9 and 63.2% in 1992 and 42.3, 64.9 and 65.1 in 1994. Similar trend was also observed at the 40 kg N ha^{-1} (Fig. 7). The effects of PM and MB residues on NUE were only marginal.

Soil Moisture

The soil moisture varied from nearly 20 mm 100 cm^{-1} profile to 100 mm 100 cm^{-1} profile during the cropping seasons in all the years. Effect of crop residues or FYM incorporation on soil moisture were perceptible during intermittent rainless periods only (Fig. 8) and the values of soil moisture, were highest in plots amended with PM residues followed by those amended with MB residues, FYM and CB residues. By the end of cropping season these differences in soil moisture levelled off due to utilization of available soil moisture by crop.

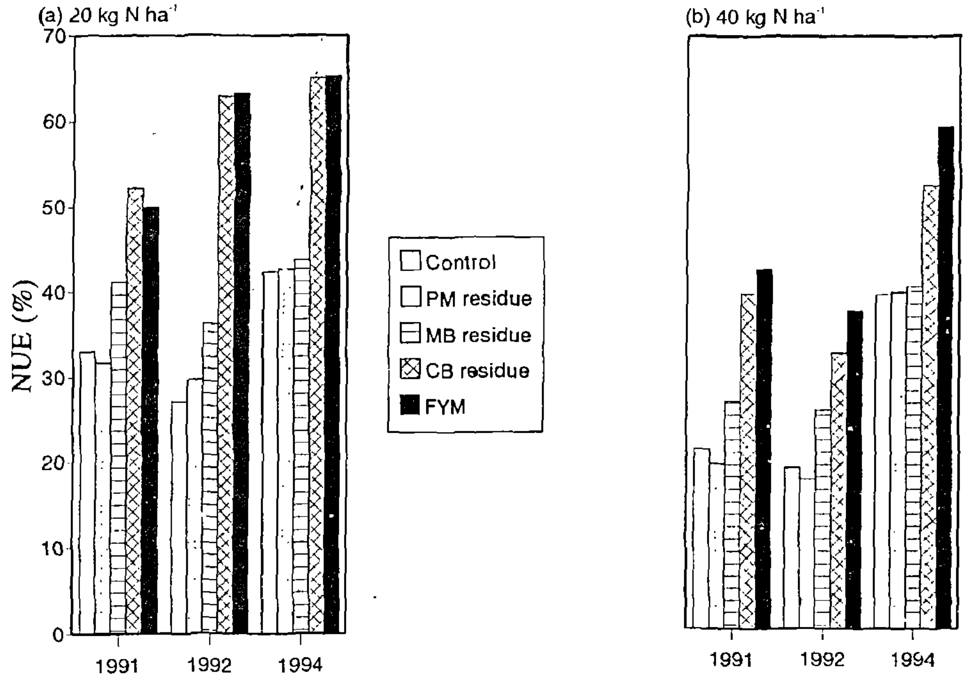

Figure 7. Effect of crop residues (PM - pearl millet; MB - mung bean and CB - clusterbean) and farmyard manure (FYM) on nitrogen use efficiency (NUE) of pearl millet in different years at 20 (a) and 40 (b) kg N ha^{-1}.

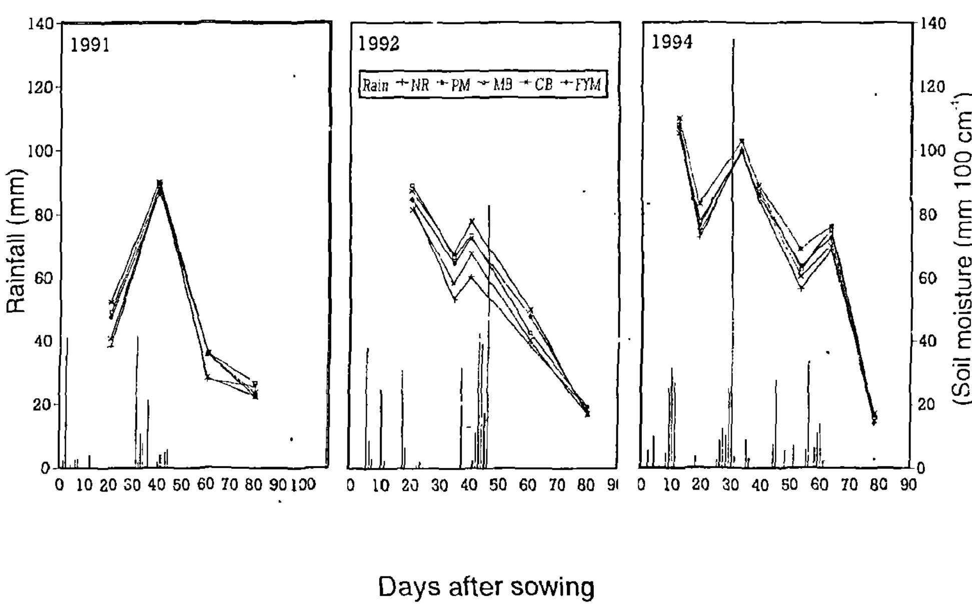

Figure 8. Effect of crop residues (PM - pearl millet; MB - mung bean and CB - clusterbean) and farmyard manure (FYM) on soil moisture in cropping period.

Organic-C changed very slowly after incorporation of crop residues and FYM (Table 7). Maximum increase from 0.19 % to 0.25% after 4 years of successive incorporation, was observed in plots amended with FYM. It was followed by plots where CB, MB and PM residues were incorporated. Similar trend was observed for total-N (Fig.9). In contrast to the total-N, the different organic forms of N showed greater variation. Continuous pearl millet cultivation without residues lead to a 17%, 27%, 14% and 3% decline in the status of hydrolyzable NH_4-N, hexosamine-N, amino acid-N and total hydrolyzable-N, respectively whereas pearl millet cultivation with crop residues or FYM increased these N fractions (Fig.9). Maximum increase, however, was observed after FYM followed by CB, MB and PM residues incorporation.

Status of available N and P was also maximum in plots amended with FYM or CB residues, whereas content of micro-nutrients remained largely unaltered (Table 7). Bio-chemical properties like dehydrogenase activity, acid and alkaline phosphatase and biomass-C showed marginal increase after incorporation of FYM and crop residues (Table 8).

Table 7. Changes in the status of organic-C, available nutrients in soil after 2 and 4 years of successive incorporation of crop residues and farmyard manure.

Duration/ Treatment	Organic C (%)	Available nutrients ($\mu g\ g^{-1}$)					
		N	P	Fe	Zn	Cu	Mn
Initial	0.19	67.6	7.1	2.01	0.30	0.17	5.32
After 2 year							
Control	0.18	66.9	6.7	2.00	0.30	0.18	5.28
Pearl millet residue	0.20	67.5	6.1	1.97	0.31	0.17	5.33
Mung bean residue	0.20	68.7	7.3	2.03	0.30	0.18	5.35
Clusterbean residue	0.20	71.4	8.7	2.09	0.32	0.17	5.36
Farmyard manure	0.21	74.3	9.2	2.09	0.37	0.18	5.41
LSD (p = 0.05)	0.02	4.1		0.07	0.07	0.04	0.15
After 4 year							
Control	0.18	67.1	7.3	2.00	0.30	0.17	5.37
Pearl millet residue	0.20	69.4	6.8	2.03	0.32	0.17	5.32
Mung bean residue	0.20	70.1	7.5	2.06	0.32	0.17	5.34
Clusterbean residue	0.23	73.4	8.8	2.10	0.35	0.18	5.38
Farmyard manure	0.25	75.4	9.3	2.13	0.38	0.19	5.45
LSD (p = 0.05)	0.03	4.3	0.9	0.09	0.11	0.05	0.19

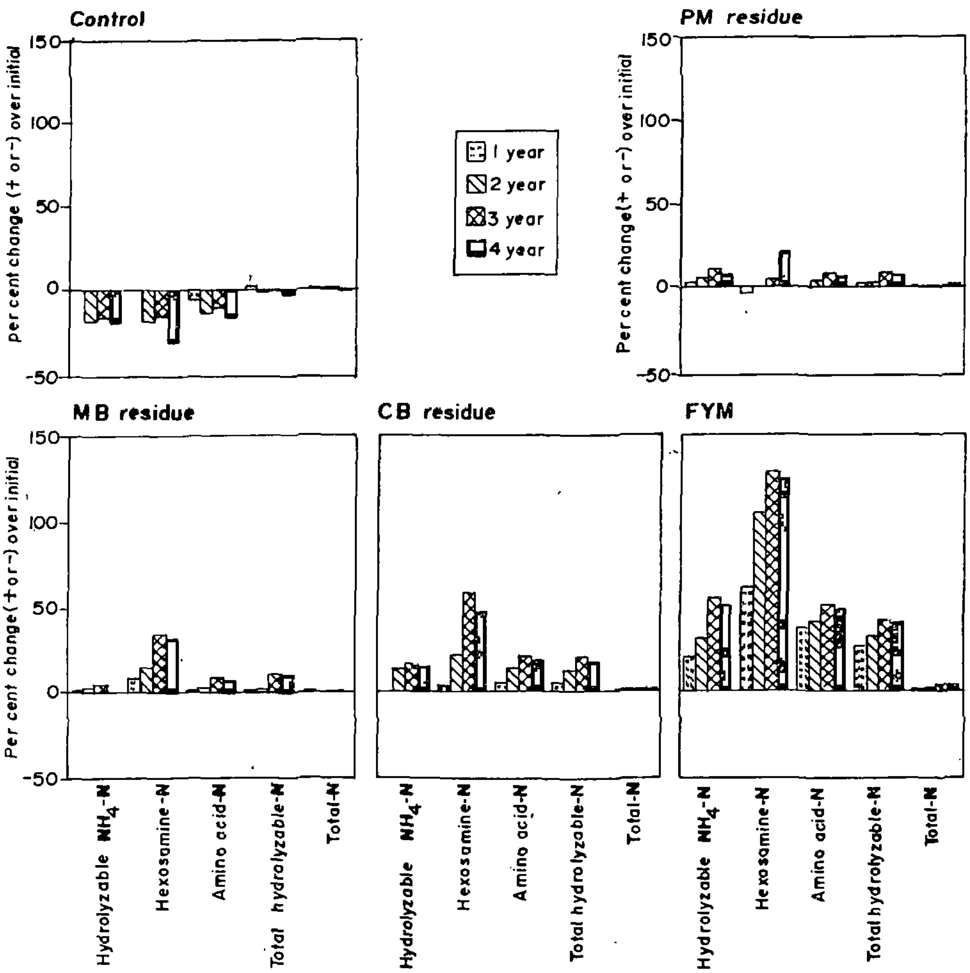

Figure 9. Effect of crop residues (PM - pearl millet; MB - mung bean and CB - clusterbean) and farmyard manure (FYM) on changes in organic fractions of nitrogen in the soil.

Table 8. Changes in the activities of different enzymes in soil after 2 and 4 years of successive incorporation of crop residues and farmyard manure.

Duration/ Treatment	Dehydrogenase ($pKat\ g^{-1}$)	Phosphatase (n Kat 100 g-1) Acid	Alkaline	Biomass-C ($\mu g\ g^{-1}$)
Initial	7.68	1.57	2.98	173.1
After 2 year				
Control	8.23	1.60	3.10	172.6
Pearl millet residue	9.27	2.92	3.67	178.2
Mung bean residue	9.70	2.63	3.61	188.6
Clusterbean residue	10.07	2.97	3.49	189.3
Farmyard manure	11.03	4.10	6.97	192.7
LSD (p = 0.05)	0.30	0.37	0.28	7.8
After 4 year				
Control	8.9	2.17	3.21	180.7
Pearl millet residue	9.8	3.05	3.69	180.7
Mung bean residue	10.7	2.91	3.73	192.6
Clusterbean residue	11.2	3.48	3.67	203.2
Farmyard manure	13.1	4.83	7.48	205.4
LSD (p = 0.05)	0.41	0.43	0.31	8.6

These results clearly indicated that incorporation of CB residues was effective in increasing crop yield and improving soil fertility. Efficacy of this residue was comparable with FYM. Addition of residue with wide C:N ratio had marginal effect on yield and soil fertility.

Discussion

Low grain yields obtained in 1991 and 1992 may be attributed to frequent water stress and to poor distribution of precipitatioin, respectively. Resowing of the crop, in part of the plot in 1992 and consequent exposure of crop to drought at later stages also might have contributed towards low yields in that year. Good crop yield was obtained in 1994 due to evenly distributed rainfall. The effect of crop residues incorporation on the pearl millet yield was in contrast to their effect on soil moisture. Although higher moisture was conserved by PM and MB residues, yield was higher under CB and FYM. This may largely be attributed to the narrow C:N ratio of CB and FYM and the resultant higher contribution to available N pool (Alexander, 1977; Vigil *et al.*, 1991). Higher yield under CB than the other two residues may also be due to the availability of high leaf content that decompose rapidly, resulting in faster mineralization of N. The significant positive effect of FYM on PM yield has also been reported by Singh *et al.*, (1981). These results thus indicate that in this region the aspect of nutritional stress to crop is no less important than the moisture stress. This view is also supported by the increase in yield levels after additional increament of N supply through fertilizers.

Nitrogen use efficiency (NUE) was low in 1991 and 1992 due to poor crop growth and low N requirement as a consequence of long spells of moisture stress but the values were higher in 1994 as evenly distributed rainfall lead to better crop growth. These values of NUE were close to those reported by Aggarwal and Praveen-Kumar (1995) under different rainfall situations. The addition of CB residue and FYM along with fertilizer N remarkably increased the NUE of applied N. Hornick and Parr (1987) have also reported improvement in NUE of the applied N in presence of organic manures and attributed it to the higher moisture availability and biological activity. In the present study though all the residues improved the soil moisture but only CB residue significantly improved the NUE.

The addition of crop residues and FYM only marginally increased the soil organic-C, indicating the oxidation of a large part of added C in soil (Doran, 1980). Similarly, the changes in the total soil N were also not significant. But changes in status of the available and organic N fractions in soil were more clear. Maximum increase in available-N and major N fractions was observed after the incorporation of FYM followed by CB residues. Similar trend observed in case of dehydrogenase activity, indicated enhanced biological activity after residue incorporation. The enhanced biological activity may be the reason of alterations in the distribution pattern of different organic N fractions (Fig. 9). These alterations must have changed their contribution towards available N. CB residues and FYM also improved the status of available-P in soil that may be due to the increased phosphatase activity (Table 8). The improvement in fertility status of soil following residue incorporation has also been reported by Prasad and Power (1991) and Geiger *et al.*, (1992) in the Sahelian soil.

On the basis of these results it can be concluded that the organic sources like CB residue with low C:N ratio can be effectively used in increasing the pearl millet yield and efficacy of this residue is comparable with that of FYM (2.0 t ha^{-1}) or 20 kg N alone. Higher yields may be achieved by the application of 40 kg N in conjunction with CB residue. Use of other residues like PM and MB with wide C:N ratio offer only limited benefit. Due to compulsion of farmers, PM residues are rarely left in field in view of their feed value.

Beneficial effect of clusterbean based cropping systems on pearl millet yield, as observed in case of first experiment may also partly be attributed to incorporation of leaf residue under field conditions.

For Managing Soil Borne Diseases

Moisture stress under rainfed conditions favor occurrence of charcoal or dry root rot caused by *Macrophomina phaseolina* (Tassi) Goid - a serious disease of many legume and oilseed crops grown in arid and semi arid regions of India (Lodha *et al.*, 1986). In order to minimize the disease incidence, inoculum density must be reduced in the soil by adopting various crop management practices (Lodha, 1996). Incorporation of organic amendments and crop residues in the soil is one such approach through which population densities of soil borne pathogens can be minimized. Information on the influence of residues of alternate crops on soil populations of *Macrophomina* could aid in planning crop rotation strategies to decrease disease severity when infested fields are rotated back into susceptible crops.

During summer months in arid regions of India, temperature of bare soil often reaches 50-60°C but even this high temperature is ineffective in reducing the viability of sclerotia of *Macrophomina* because the soil remains dry (Lodha *et al.*, 1990). Since soil moisture greatly affects the sensitivity of resting structures to heat treatment (Katan *et al.*, 1976), merely by one summer irrigation, a reduction of 25-42% could occur in the population of *Macrophomina* (Lodha and Solanki, 1992; Lodha, 1995). Solarization of moistened soil further augmented this reduction in the top soil layer but still many propagules survived in lower soil depths (Lodha and Solanki, 1992).

Amending of soil with cruciferous residues can suppress certain soil borne pathogens and root diseases (Angus *et al.*, 1994; Gamliel and Stapleton, 1993; Muehlchen *et al.*,1990). Combining solarization with these amendments improved control of *Fusarium oxysporum* f. sp. *conglutinans* (Ramirez-Villapudua and Munnecke, 1987, 1988). Such information on the effects of cruciferous residues combined with moisture and high soil temperature for *Macrophomina* is not available.

Scarcity of moisture, low microbial population and high temperature of arid region prolongs the process of decomposition of crop residues, when incorporated directly in the nutrient deficient sandy soil. Another disadvantage of direct incorporation is that crop residues at times may carry plant pathogens (Dalzell *et al.*, 1987). Composting is an alternate method of inactivation of pathogens and decomposing crop residues more rapidly. Studies have shown that many pathogens were completely inactivated but a few heat tolerant pathogens could survive during the heat phase of composting (Bollen *et al.*, 1989; Ylimaki *et al.*, 1983).

Macrophomina survives in the soil primarily as sclerotia formed in infected plant during parasitic phase and released into the soil after disintegration of host tissues (Cook *et al.*, 1973). The infected crop residues thus become the main carrier of sclerotia and increases the population of *Macrophomina* in the field (Cook *et al.*, 1973; Meyer *et al.*, 1973). Concerned with the risk of spreading *Macrophomina* by amending compost in the soil, we analysed several samples from on-farm composts and detected 60-80 sclerotia g^{-1} of compost. Since *Macrophomina* is a heat tolerant pathogen (Bega and Smith, 1962; Mihail and Alcorn, 1984), efforts are, therefore required to eliminate or bring down the sclerotial population of *Macrophomina* below the economical threshold level in composted material before incorporating into the soil.

Experiments were therefore, initiated to study the effect of crop residues on population dynamics of *Macrophomina* under laboratory conditions. In another set, field studies were undertaken to evaluate the efficacy of cruciferous residues combined with summer irrigation and/or solarization on the population of *Macrophomina* within a short period.

Composts have been used with various levels of success for suppression of soil borne plant pathogens (Hoitink and Fahy, 1986).

Experiments were also carried out to study (i) factors that can influence release and inactivation of *Macrophomina* from crop residues in soil vis-a-vis during composting and (ii) efficacy of composts as soil amendment on microbial population including *Macrophomina* and antagonists, dry root rot incidence and seed yield of clusterbean.

Experimental Procedures

A. Efficacy of Residues in Conjunction with Nitrogen on *Macrophomina* Population

Three levels (equivalent to 20, 40 and 60 Kg N ha^{-1}) of residues of pearl millet and clusterbean were incorporated in the soil amended with or without 40 kg N ha^{-1} under laboratory conditions. Population changes in *Macrophomina*, total bacteria, total actinomycetes and total fungi were followed for three months at 30-day interval using standard procedures on Chloroneb-Mercury-Rose bengal-Agar (CMRA medium) (Meyer *et al.*, 1973), Thornton's agar, and Martin's Rose Bengal agar. NO_3-N was estimated at the same intervals by extracting the soil with 2M KCl. Extracted samples were then analysed by a flow-injection-analyser (Tecator).

B. Efficacy of Pearl Millet Residues and Oil-cakes on *Macrophomina* and *Fusarium* Population

Sclerotia of *Macrophomina* and spores of *Fusarium* were produced separately on 5% maize meal:sand medium and then mixed uniformly with 5 kg of the field soil to establish populations of *Macrophomina* and *Fusarium* of 2753 g^{-1} propagules and 330 g^{-1} spores, respectively. The population of *Macrophomina* was determined as described earlier while that of *Fusarium* on modified peptone-PCNB medium (Papavizas, 1967). Total microbial populations in soil were enumerated using standard procedures. Each sample was analysed in six petri plates.

The infested soil was sub-divided into many lots for mixing with most promising residue identified on the basis of earlier experiment i.e. pearl millet residue (PMR at 0.9% - equivalent to 60 kg N ha^{-1}) enriched with urea (40 kg N ha^{-1}), mustard cake (MC at 1%) and castor cake (CC at 1%) separately and a combination of the above. The six treatments were (1) N+PMR (2) N+PMR+MC (3) N+PMR+CC (4) MC (5) CC; (6) infested non amended soil only. The moisture level in all the treatments was maintained at 50% of the WHC throughout the experiment. Amended and non-amended soils were incubated at $28\pm2^{o}C$ in punctured polythene bags (three replicates per treatment). Each bag was punctured 10-12 times with paper pins to allow air exchange. A soil sample of about 10 g was withdrawn from each bag up to 60 days at 15 day intervals and air dried for 24 h to estimate population densities of *Macrophomina, Fusarium* and total microbes.

Populations of actinomycetes and bacteria antagonistic to pathogenic fungi were enumerated on Czapeck Dox agar (pH 7.2) against *Macrophomina* and *Fusarium* separately (Ghaffar *et al.*, 1969).

C. Combined Effects of Residues, Soil Solarization and Summer Irrigation on *Macrophomina* Population

Macrophomina was isolated from the diseased roots of clusterbean and multiplied on *Prosopis*-potato broth (Bohra *et al.*, 1998) for 10 days at $30\pm2^{o}C$. Harvested sclerotia were added to 1 kg of soil and left for *10 days. The infested soil was passed through a 300 mesh (53 μm)* sieve. The residue soil left in the sieve containing only sclerotia was then mixed in 48 kg of soil. Two kg portions of *Macrophomina* infested soil were mixed uniformly up to 30 cm depth in each of 28 sub-plots (3x1 m) in April, 1994. After 7 days, three soil samples to a depth of 30 cm were collected randomly from each of the sub-plots and sclerotial population of *Macrophomina* was estimated. Eight sub-plots were amended to the same depth with mustard cake (4 ton ha^{-1}) and equal number with cauliflower residue (CF, 5 ton ha^{-1}).

On 10th May, one irrigation was applied in all the sub-plots except control. Four sub-plots of each amendment and irrigated plots were covered with 50 μm polyethylene sheets. Soil temperatures were recorded at 7.5 and 22 cm depth at an interval of 2 h from 10 to 16 h. Polyethylene sheets were removed after 15 days. Soil samples were collected from the depth of 0-15 and 16-30 cm. Half of each sample was used for moisture determination while the remaining was used for counting *Macrophomina* propagules and lytic bacteria (Greenberger *et al.*, 1987).

D. Efficacy of Composts Prepared from Crop Residues on *Macrophomina* Population and Dry Root Rot Incidence on Clusterbean

Compost from the residues of PM, CB, CF and a mixture of off-season weeds (WC) were prepared in separate pits (1.7 m^{-3}) under partially anaerobic conditions adopting layer system. In each pit 30 cm layer was filled with 40 kg of residues enriched with 1% gypsum (400 g) and a solution of 2 % urea (800 g). Each layer was provided with 60 % moisture and then covered with 10 cm thick layer containing a mixture of cowdung (68 kg) and field soil (100 kg). Initial C:N ratios of all the residues, cowdung and soil were determined. In clusterbean and pearl millet compost pits, several 20 g samples each containing 2 g pieces (0.5 - 1.5 cm) of infected roots and 18 g apparently healthy residues, enriched with 2 or 4% urea-N, were placed in small nylon pouches (120 μm pore). These were buried at 30 and 60 cm depth. Temperatures were recorded every day till 6 weeks. Pouches were retrieved from pits after 2 and 4 months to estimate viable propagules of *Macrophomina*.

In order to study the release and survival of *Macrophomina* from residues in the soil, two sub-samples (2 g infected + 18 g healthy residues) each mixed in 100 g soil, were placed in punctured polyethylene bags and incubated at 30±2°C. Soil-residue mixture was maintained at 50% of WHC. A 5 g sample was withdrawn after 2 and 4 months or when final composting was over to estimate *Macrophomina* propagules.

Composted materials were taken out from pit after decomposition. Three samples (500 g) were collected randomly from each compost to estimate C:N ratio, *Macrophomina* and microbial population including antagonists. To study effect of natural summer heating of composts on the population density of *Macrophomina*, composts were separately spread over soil surface as a 10-12 cm thick layer in an open field during hot summer days of June and moistened at 10% (w/v) with water. Temperatures (5 cm depth) were recorded every day at 1400 h. After seven days of exposure, three samples (50 g) were collected randomly from each compost and processed for the estimation of *Macrophomina* population.

Efficacy of composts against dry root rot was studied for two years in a fixed layout using completely randomized block design with five replications. After natural heating, composts of pearl millet (PMC), clusterbean (CBC), weeds (WC) and cauliflower residues

(CFC) each @ 4 ton ha^{-1} were incorporated in separate plots (4x4 m). Clusterbean (cv. HG 75) was sown on 25th and 22nd July in 1994 and 1995, respectively. Three soil samples at same depth from each plot were collected, before amending and 15 days after harvest and processed for biological assays. Data on plant mortality due to dry root rot were recorded 12-15 days before harvest. Seed yield of clusterbean was also recorded.

Accomplishments

A. Efficacy of Residues in Conjunction with Nitrogen on *Macrophomina* Population

There was a sharp decline in the population of *Macrophomina* in all the treatments amended with crop residues and or nitrogen even at first interval of sampling. The per cent decrease in *Macrophomina* population was significantly higher in all the treatments having pearl millet residues (PMR) amended with nitrogen as compared with clusterbean residues (CBR) or non amended treatments. Among three levels of PMR, maximum decrease (96.3%) in the population of *Macrophomina* was estimated in the level 2 (equivalent to 40 kg N ha^{-1}) at 90 days (Table 9). An inverse relationship was observed between the increase in microbial population and the decrease in *Macrophomina* population.

Table 9. Population changes in *M. phaseolina* (MP), total bacteria (TB) and actinomycetes (TA) in the soil ameded with crop residues and nitrogen after 90 days.

Crop residue levels (=N kg ha^{-1})	Levels of added nitrogen (kg ha^{-1}) 0			40		
	Population g^{-1} soil					
	MP ($x10^3$)	TB ($x10^5$)	TA ($x10^5$)	MP ($x10^3$)	TB ($x10^5$)	TA ($x10^5$)
Clusterbean						
20	130	73	56	100	61	40
40	100		28	30	68	37
60	80	58	56	75	69	50
Pearl millet						
20	45	36	26	35	68	33
40	95	50	22	20	46	23
60	75	45	24	25	82	30
Control	180		12	135		34
Initial soil	550	7.5	10.2	550	7.5	10.2

The results of soil chemical analyses indicated that whole of the urea added alone was recoverd as NO_3 on the 30th day which declined thereafter (Table 10). In the absence of added N slight increase in the NO_3-N was estimated up to 60th day. After the addition of CB residues this trend continued upto 90th day but the concentration declined on 120th day. No such increase in NO_3-N content was observed after addition of PM residues without additional N. However, when CB residues were added along with urea-N the quantity of NO_3-N from 30th day onwards was less than that estimated in case of urea alone. It decreased with increasing level of CB residue.

Table 10. Periodic changes in NO_3-N in soil ($\mu g\ g^{-1}$) after incorporation of urea, crop residue and their combination.

Treatment	Sampling (days)				
	15	30	60	90	120
Control	0.75	2.04	4.24	0.43	0.20
Urea (N40)	1.44	18.96	16.82	14.50	10.75
CB1+N0	0.37	0.65	2.27	3.40	0.05
CB2+N0	0.22	0.27	1.22	3.32	0.11
CB3+N0	0.20	0.60	0.47	2.31	0.30
CB1+N40	1.25	6.95	9.22	13.38	4.34
CB2+N40	0.99	4.76	7.13	10.37	3.24
CB3+N40	0.92	3.81	5.94	8.30	1.11
PM1+N0	0.54	0.36	0.89	0.24	0.14
PM2+N0	0.12	0.30	0.21	0.30	0.24
PM3+N0	0.17	0.43	0.08	0.30	0.19
PM1+N40	1.10	2.14	7.56	0.47	0.14
PM2+N40	0.43	0.78	3.21	0.42	0.07
PM3+N40	0.21	0.36	0.64	0.36	0.05

Pearl millet (PM) and Clusterbean(CB) residue; 1, 2 and 3 represent residues equivalent to 20, 30 and 40 kg N ha^{-1} .

B. Effect of Pearl millet Residue and Oil-cakes on *Macrophomina* and *Fusarium* Population

A significant reduction in the population of *Macrophomina* occurred in the cake and pearl millet residue amended soil (Table 11). In the MC alone and N+PMR+MC amended soil, 100% reduction was achieved within a period of 30 and 45 days, respectively. In N + PMR amended soil, numbers of viable propagules of *Macrophomina* were reduced by 94% in 45 days.

The population of *Fusarium* showed a dramatic rise ($13\text{-}92 \times 10^{-3}$) after 15 days in all the cake amended treatments. However, in MC amended soil a 100% reduction was achieved within 30 days. After 60 days, the population had declined in all the treatments (Table 12). Contrary to the effect on *Macrophomina*, the population of *Fusarium* in the infested soil without amendments showed a gradual increase. Incorporation of N+PMR in MC and CC maintained higher populations of *Macrophomina* and *Fusarium* than when the cakes were added separately.

Table 11. Effect of soil amendments on population of *Macrophomina*, total number of bacteria and fungi and the antagonistic acitnomycetes population g^{-1} soil after 45 days.

Amendments[a]	*Macrophomina*	Bacteria ($\times 10^6$)	Fungi ($\times 10^4$)	Antagonistic actinomycetes($\times 10^6$)
N+PMR	152	109	14	4.3
N+PMR+MC	0	145	23	23.3
N+PMR+CC	366	164	16	38.3
MC	0[b]	162	8	27.3
CC	200	243	2	24.0
None	1132	143	2	2.3
LSD (p= 0.05)	116	9	2	4.4
Initial Population	2753	87	1	0.7

[a] N - Nitrogen(40 kg ha^{-1}) as urea; PMR - pearl millet residue (0.9%); MC - mustard cake (1%); CC - castor cake (1%).
[b] Same as after incubation for 30 days.

Table 12. Effect of soil amendments on population of *Fusarium*, total numbers of bacteria and fungi and the antagonistic actinomycetes population g^{-1} soil after 60 days.

Amendments[a]	*Fusarium* ($\times 10^3$)	Bacteria ($\times 10^6$)	Fungi ($\times 10^4$)	Antagonistic actinomycetes ($\times 10^6$)
N+PMR	1.3	136	16	4.3
N+PMR+MC	8.3	209	20	20.6
N+PMR+CC	2.0	634	19	14.5
MC	0[b]	240	4	11.0
CC	1.3	486	3	6.6
None	1.7	94	4	0.3
LSD (p= 0.05)	1.9	84	3	2.4
Initial Population	0.3	87	1	0.3

[a] N-Nitrogen (40 kg ha^{-1}) as urea; PMR-pearl millet residue (0.9%); MC-mustard cake (1%); CC-castor cake (1%)
[b] Same as after incubation for 30 days.

The total population of fungi was also significantly higher in all treatments having N+PMR (Table 11 and 12). The population of bacteria and actinomycetes increased considerably in amended soils. Over 90% of the total number of actinomycetes were antagonistic to *Macrophomina*, with the highest numbers in the N+PMR+CC amended soil. However, populations of actinomycetes antagonistic to *Fusarium* propagules were less as compared with *Macrophomina*. The number of bacterial antagonists did not differ significantly in amended soils.

C. Combined Effects of Residues, Soil Solarization and Summer Irrigation on *Macrophomina* Population

During the 15 days period of experimentation, maximal air temperature ranged from 37.9 - 47.4°C, solar irradiation 9.78-12.8 $MJm^{-2}d^{-1}$, available sunshine 9.4-11.9 h d^{-1} and evaporation 10-19.2 mm water d^{-1}.

Soil temperature at 1400 h was higher than at 1600 h at 7.5 cm depth but at 22 cm the reverse was true. Maximal temperature of dry soil (DS) during the experimental period reached up to 53°C (7.5 cm) and 46°C (22 cm) (Table 13). This natural heating of dry soil could reduce propagules by only 10.9%.

Table 13. Soil temperature ranges recorded during soil solarization period[a].

Treatments[b]	Temperature (oC)	
	Depth (cm)	
	7.5	22.0
MC/CR + SI+S	48-57	42-50
MC/CR+SI+NS	46-53	38-47
SI+S	48-56	41-49
SI	45-51	38-46
DS	49-53	39-46

[a] 11-25 May, 1994
[b] MC/CR - mustard cake or cauliflower residue,SI - Summer irrigation at field capacity (10.4% w/w) on 10th May, S - Solarized, NS - Non-solarized and DS - Dry soil.

Application of summer irrigation (SI) in the dry plots (without amendment) initially decreased the soil temperature to 37°C but it increased gradually and reached 51°C (7.5cm) and 46°C (22 cm) within 6 - 7 days. This resulted in the reduction of approximately 40% of viable counts of *Macrophomina* in 0-30 cm soil depth. In non-amended irrigated solarized plots (SI+S) temperature was 3-7°C higher than corresponding control. Increased soil temperature drastically reduced the viable propagules at 0-15 cm but was only partially effective at lower soil depth (Table 14).

Table 14. Effect of summer irrigation, soil solarization and cruciferous amendment on the reduction of *M. phaseolina* population in soil[a].

Treatments[b]	Initial and Final *Macrophomina* counts (g^{-1} soil) and % reduction			
	0 - 15 cm depth		16 - 30 cm depth	
	Sclerotia	% Reduction	Sclerotia	% Reduction
MC +SI + S	11.6 (1003)[c]	98.7 (83.63)[d]	31.6 (1003)	97.0 (80.13)
MC + SI + NS	38.3 (947)	95.8 (78.43)	67.5 (947)	93.6 (75.51)
CR + SI + S	7.0 (863)	99.2 (85.04)	12 (863)	98.5 (83.21)
CR + SI + NS	103.0 (1110)	90.4 (72.21)	265 (1110)	74.7 (60.23)
SI + S	117.3 (1048)	88.8 (70.50)	321.7 (1048)	69.3 (56.37)
SI	547 (943)	42.2 (40.40)	588 (943)	37.6 (37.80)
DS	977.1 (1093)	10.6 (9.10)	970 (1093)	11.2 (19.36)
LSD (p = 0.05)		4.06		

[a] Soil solarization period : 11-25 May 1994.
[b] MC- mustard cake (4 ton ha^{-1}), CR-cauliflower residue (5 ton ha^{-1}), SI- summer irrigation at field capacity (10.4 % w/w) on 10th May, S- solarized, NS- non-solarized and DS- Dry soil
[c] Initial population of *Macrophomina* (average of three replications)
[d] Arcsine square roots.

In all the treatments having amendments, for the first 6 days, soil temperature remained 1 - 2°C higher than corresponding non-amended plots. Amendment of soil with cruciferous residues (mustard cake and cauliflower) augmented the efficiency of summer irrigation by eliminating a sizable proportion of *Macrophomina* propagules in non-solarized plots even under the similar soil temperature conditions and the level of reduction in mustard cake amended plots was statistically equal in both the soil depths (Table 14). Efficacy of mustard cake under the influence of summer irrigation has also been illustrated separately in Fig. 10.

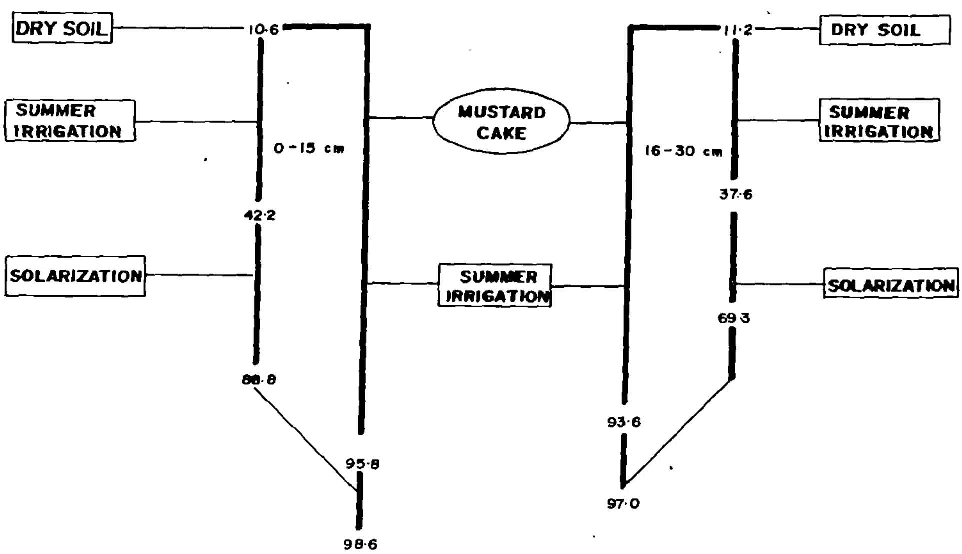

Figure 10. Per cent reduction in Macrophomina phaseolina propagules by summer irrigation, solarization and combined effect of mustard cake at 0-15 and 16-30 cm soil depth.

Soil solarization of amended and irrigated plots elevated the maximum soil temperature by 4-6^{o}C than the corresponding control. As a result of combined effects of moisture, amendments and temperature, almost complete eradication of viable propagules of *Macrophomina* also occurred at lower soil depth.

Cruciferous residues increased the population of lytic bacteria to a small extent in irrigated non-solarized soil but their density increased significantly in amended solarized soil particularly at 0 - 15 cm depth (Table 15). In general, a significantly higher density of lytic bacteria was found in mustard cake than cauliflower residue amended soil at 16-30 cm soil depth.

Table 15. Lytic bacterial density against *Macrophomina* in non-solarized and solarized amended soil[a].

Treatments[a]	Lytic Bacterial Density ($x10^5$ CFU ml^{-1})	
	0 - 15 cm	16 - 30 cm
MC + SI + S	40.6	68.8
MC + SI + NS	17.8	48.6
CR + SI + S	47.6	18.8
CR + SI + NS	21.0	19.6
SI + S	35.8	17.9
SI	15.3	12.3
DS	13.3	11.0
LSD (p = 0.05)	8.0	

[a] MC - mustard cake , CR- cauliflower residue, SI- summer irrigation S- solarized, NS - non- solarized and DS - dry soil, CFU - colony forming unit

D. Efficacy of Composts Prepared from Residues on *Macrophomina* Population and Dry Root Rot Incidence on Clusterbean

The process of composting was completed in all the pits in a period of 5 - 6 months. The maximum temperature varied from 48 - 51°C at 30 cm and 60 - 62°C at 60 cm depth. The heat phase lasted 3 to 4 weeks. In general, considerable decrease in C:N ratio was estimated in all the final products (Table 16).

Table 16. C:N ratio of residues-soil-dung-urea mixture (compost mixture) and their composts.

Compost mixture	C : N ratio	
	Initial	Final
Pearl millet	27.3	18.2
Clusterbean	30.9	9.4
Weeds	26.8	9.4
Cauliflower leaves	15.1	11.6

C:N ratio of each residues and other components are as follows:
Pearl millet = 83.3, Clusterbean = 64.5, Weeds = 57.3 and
Cauliflower leaves - 19.6, Urea = 0.43.

Moisture level was maintained up to 60% throughout experimentation. Total microbial and bacterial populations were maximum in cauliflower compost but actinomycetes and fungi were significantly higher in clusterbean compost (Table 17). Lytic bacterial density and actinomycetes antagonistic to *Macrophomina* were signifi cantly higher in clusterbean followed by cauliflower compost compared

Table 17. Population status of resident microflora of composts.

Compost	*Macrophomina* (g^{-1}compost)	Lytic bacteria ($x10^5$CFU ml^{-1})	Bacteria ($x10^6g^{-1}$ compost)	Actinomycetes ($x10^5g^{-1}$ compost)	Fungi ($x10^3g^{-1}$ compost
Pearl millet	67	130	35.5	1.3	11.5
Clusterbean	45	171	27.0	5.0	41.5
Weeds	55	142	30.7	1.3	23.2
Cauliflower leaves	31	156	43.3	1.3	7.0

CFU - colony forming units

to other two composts. In completely composted material viable sclerotia of *Macrophomina* were minimum in cauliflower and maximum in pearl millet compost. The average native population of *Macrophomina*, in the soil used in compost pit was 135 sclerotia g^{-1}. There was a significant reduction in the population of viable sclerotia of *Macrophomina* in the partially decomposed clusterbean residue samples retrieved from 60 cm depth compared to those from 30 cm depth in both, pearl millet and clusterbean compost pits (Fig.11). The reduction was significantly higher in the residues enriched with 4% compared to 2% N and in clusterbean compared to those placed in pearl millet pit.

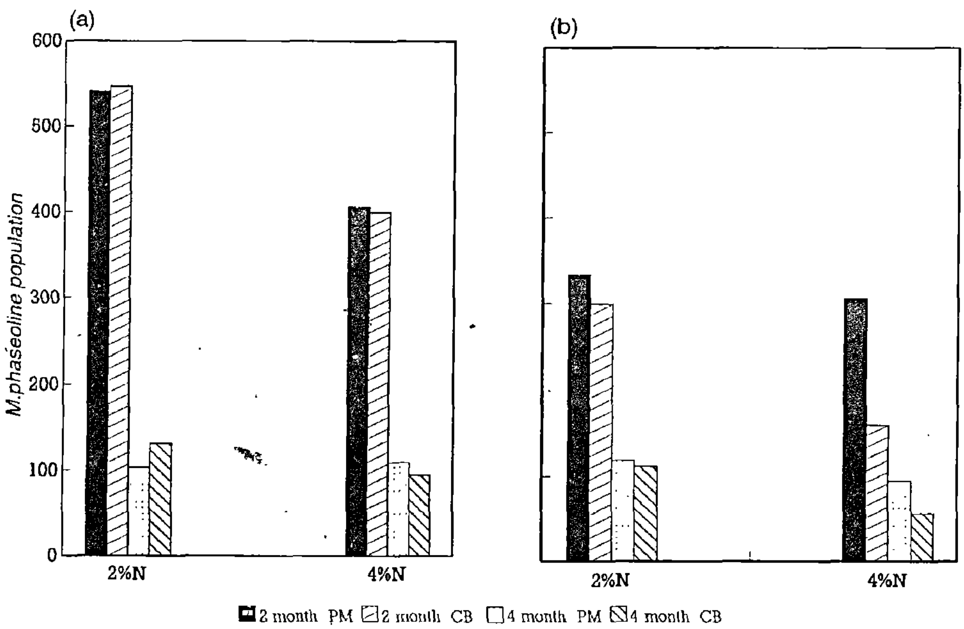

Figure 11. Survival of Macrophomina phaseolina in the infected clusterbean residue samples enriched with 2 and 4% urea-N buried at (a) 30 cm and (b) 60 cm soil depth and retrieved after 2 and 4 months from pearl millet (PM) and clusterbean (CB) residue compost pits.

A large number of sclerotia of *Macrophomina* were released in soil from partially decomposed clusterbean residues after 2 months of incubation (Table 18). However, after 4 and 6 months of incubation, a drastic reduction in the viable propagules was recorded that was more in residues enriched with 4% compared to 2% N.

Table 18. Release of *Macrophomina* propagules during decomposition of infected residues at 50% WHC in arid soil.

Decomposition gradient	Months	*Macrophomina* population (g^{-1} residue-soil) Urea (%) 2	4
Partial	2	4836	3971
Almost	4	3531	2735
Complete	6	2273	1381

Native *Macrophomina* population in soil : 135 g^{-1} soil

During 7 day period of summer exposure, maximai temperature of composts reached up to 53°C at 5 cm depth within 2-3 days. As a result, 53-61% reduction in counts of *Macrophomina* was estimated in different composts (Table 19) that were considered suitable for field amendment.

Table 19. Effect of additional moisture and natural heating on population changes of *Macrophomina* in different composts.

Compost	*Macrophomina* propagules (g^{-1} compost)
Pearl millet	31
Clusterbean	18
Weeds	23
Cauliflower leaves	12

The incidence of dry root rot in 1994 was not severe on clusterbean crop due to more and evenly distributed rainfall during the growing season. However, a long duration of moisture stress after sowing (27 day dry spell) caused severe plant mortality due to dry root rot in 1995. In both the years, minimum plant mortality and maximum seed yield were recorded in the cauliflower compost amended plots (Table 20).

Table 20. Dry root rot mortality induced by *Macrophomina* and grain yield of clusterbean (1994)

Compost amended soil	Mortality (%)	Grain yield (kg ha^{-1})
Pearl millet	2.0	508.3
Clusterbean	3.0	572.7
Weeds	4.2	585.7
Cauliflower	2.2	604.1
Control	5.4	396.5

In general, amendment of compost increased population of antagonistic actinomycetes and lytic bacteria that accompanied decrease in the population of *Macrophomina* in soil (Table 21). Among composts, increase in antagonists was significantly higher in cauliflower compost amended soil which also had maximum reduction in *Macrophomina* counts. Thus an initial population of 640 propagules g^{-1} soil at the time of sowing in 1994 decreased to 253 and 381 propagules g^{-1} soil after harvest in 1994 and 1995, respectively in cauliflower compost amended soil.

Table 21: Population of antagonistic actinomycetes and lytic bacterial density in compost amended soil.

Compost	Antagonistic actinomycetes ($X10^4 g^{-1}$ soil)	Lytic bacteria ($X10^4$ CFU ml^{-1})
Pearl millet	9.5	32.0
Clusterbean	8.0	39.0
Weeds	10.0	34.6
Cauliflower leaves	20.0	38.3
Control	7.2	24.0

CFU - colony forming units

Discussion

Comparison of the effect of PMR and CBR indicated higher efficiency of PMR incorporation in the soil enriched with nitrogen in reducing the inoculum density of *Macrophomina*. Moist addition of urea (40 kg N ha^{-1}) decreased the C:N ratio and hastened the decomposition of crop residues. Periodical estimates of NO_3-N in soil (Table 10) indicated immobilization of fertilizer N added with residues upto 120 days. As C and N generally limit microbial build up in soil, availability of both under experimental conditions, would further increase microbial population and thus adversely affect *Macrophomina* population. Reduction in population of both the soil borne pathogens after amendment with oil-cakes may be due to release of toxic gases during decomposition. Apart from the toxic effect of cakes, increased populations of actinomycetes and bacteria might have also contributed in reducing the population of *Macrophomina* and *Fusarium*.

Significantly higher population of *Macrophomina* in the CC as compared with MC amended soil suggest that CC does not contain toxic substances to the level of MC. Incorporation of cruciferous residues in the soil has been known to reduce the population of soil borne pathogens effectively and the effect was mainly attributed to the release of toxic volatiles (Gamliel and Stapleton, 1993). Combining N+PMR with MC or CC maintained higher populations of *Macrophomina* and *Fusarium* than when the cakes were added separately. This observation indicates that incorporation of nitrogen enriched crop residues might have affected the release of toxic volatiles from cakes.

Amending the soil with cruciferous residues during hot summer days almost completely eradicated the population of *Macrophomina* within 15 days. In the present field study, soil temperatures at a depth of 7.5 cm remained higher than the thermal death time temperature (50°C for 1.5 h) reported for *Macrophomina* (Bega and Smith, 1962). Thus, the sharp decline in the viability of pathogenic propagules in the top layer could be attributed primarily to high soil temperatures (Sheikh and Ghaffar, 1984; Lodha and Solanki, 1992). This is also supported by the fact that temperatures at 22 cm remained relatively low (50°C) and mortality of the pathogen was also low at this depth. In dry soil, in spite of high temperatures, there was only a slight reduction in numbers of pathogenic propagules. However, summer irrigation affected the sensitivity of resting structures to heat treatment (Katan *et al.*, 1976; Lodha, 1995). The possible mechanism of control induced by irrigation in heated soil could be by dilution of the fungistatic behaviour of the soil, stimulating germination of resting structures (sclerotia), which are more vulnerable to increased heat conduction and microbial activities. In the presence of water, less energy is required to unfold the peptide chain of proteins, resulting in lower heat resistance. Germtubes and subsequent hyphae from germinating sclerotia of *Macrophomina* are sensitive to bacteria and actinomycetes, resulting in lysis of fungal walls (Kovoor, 1954).

In our experiment, an almost equal reduction within 15 days at the lower soil depth could be attributed to a combination of mechanisms. A weakening effect of sub-lethal soil temperature (47-50°C) may have facilitated the action of sulfur-containing toxic volatiles from cruciferous residues and microbial antagonism (Lewis and Papavizas, 1970; Lifshitz *et al.*, 1983). After incorporation of cruciferous residues in moist soils, a greater release of toxic volatiles such as dimethyl sulfide, mercaptan and isothiocyanate at high temperatures was reported by Gamliel and Stapleton (1993). However, isothiocyanates were not detected at low temperature (Lewis and Papavizas, 1970, 1971) and these are mainly responsible for the inhibition or reduction of soil borne pathogens (Angus *et al.*, 1994). Moreover, sharp reductions were observed in *Fusarium* counts in closed as compared to open containers (Ramirez-Villapudua and Munnecke, 1987). A mulch cover would seal the soil as in a closed container and thus would slow the release of volatiles and evaporation of water. Amendments further improved the moisture retention capacity of sandy soil and thereby increased activities of antagonistic microorganisms (Dhingra and Sinclair, 1975). Some of the volatiles released during decomposition also stimulated germination of fungi and bacteria and increased microbial activity in soil (Ramirez-Villapudua and Munnecke, 1988). A possible role of increased lytic bacterial density in reducing *Macrophomina* counts at lower soil depth in mustard cake amended soil cannot be excluded as these bacteria are capable of lysing fungal mycelium of soil-borne pathogens (Mitchell and Alexander, 1963).

A reduction to the tune of 57% in the counts of *Macrophomina* was achieved by irrigating soil amended with urea-N and farmyard manure, without mulching (Lodha, 1995). In the present study, substitution of toxic cruciferous residues for these amendments, further augmented this decline. Heating cabbage-amended soil, even at 45^{oC}, has been found effective in controlling *Pythium* and *Sclerotium* populations (Gamliel and Stapleton, 1993). In our experiment, a temperature range of 50-51^{o}C at 7.5 cm and 45- 47^{o}C at 22 cm depth in irrigated soil for more than 1 week was achieved by natural heating alone. A further increase in soil temperature occurred soon after amendment and was also reported by Gamliel and Stapleton (1993). Thus, combining amendments of cruciferous residues with one irrigation during hot summer days as a substitute for polyethylene mulching may be practical in the cultural control of *Macrophomina*. Cruciferous plants, particularly mustard, are extensively cultivated in this region and cake is also readily available as a by product of the oilseed extraction industry. Our results demonstrated a novel approach for managing soil borne pathogens in hot arid regions where intense solar irradiation, along with crop-free periods and irrigation are available during summer months.

The greater part of the inoculum of *Macrophomina* released from infected plant residues (of susceptible host) was eradicated by the integration of different approaches during and after composting. Considerably higher survival rate of sclerotia released in the soil from decomposing residues in the same period signifies the use of compost as soil amendments. Many factors may be involved in the sharp reduction of sclerotial population of *Macrophomina* during composting (i) heat generated in the first phase, (ii) toxicity of conversion products formed during or after the self-heating process (iii) availability of moisture and (iv) microbial antagonism.

In the present study, pronounced reduction in propagules, particularly at 60 cm, could be attributed to elevated temperatures (60 - 62^{0}C) during heat phase, that reached in the ranges found to be lethal for sclerotia of *Macrophomina.* This effect was also evident by the survival of relatively higher number of sclerotia in the samples kept at 30 cm depth where temperature increase was relatively low (48-51^{0}C). Further, survival of more sclerotia released from residues in the soil kept at 30^{0}C in laboratory test compared to those at 30 cm in compost pit confirmed the significant role of elevated temperatures in inactivation. However, presence of viable sclerotia in the samples retrieved from pits after 2 months indicated that heat phase alone was not sufficient to completely kill or inactivate the released propagules of *Macrophomina.* Further reduction in viable sclerotia of *Macrophomina* after the heat phase could be a result of combined effects of soil moisture, nitrogen, and microbial antagonism. In the present study, attempt to expose moistened compost to prevailing high temperatures was found highly effective in almost eliminating the remaining propagules of *Macrophomina.* A weakening effect exerted by sub-lethal temperatures (48-53^{0}C) on sclerotia of *Macrophomina* might have accelerated microbial antagonism by lytic bacteria and actinomycetes.

Amendment of composts directly benefit soil by improving soil water holding capacity, infiltration, aeration, permeability, soil aggregates, micro-nutrients and microbiological properties (Benedict *et al.*, 1988; Chang *et al.*, 1983). These results showed a quantitative and qualitative improvement in the population of bacteria and actinomycetes along with antagonists. Amended soil held more water than the non-amended sandy soil (Gattani and Jain, 1976; Lodha, 1996). Increased availability of soil moisture, in turn, reduce *Macrophomina* population due to enhanced antagonism (Dhingra and Sinclair, 1975).

These results demonstrated greater potentials of cauliflower compost amendment compared to other composts, where increased antagonists brought proportionate reduction in *Macrophomina* counts and dry root rot incidence. Increased microbial population particularly those of antagonistic actinomycetes and lytic bacteria against *Macrophomina* in compost amended soil is of long-term beneficial consequence. Bacteria may compete with germinating sclerotia for available carbon or nitrogen sources and by eliminating these resources, the bacteria reduce the percentage of sclerotial germination (Elad and Chet, 1987). Enhanced population of antagonistic actinomycetes in compost amended soil would induce suppressiveness because in fairly dry soils also their presence reduced counts of *Macrophomina* (Lodha *et al.*, 1990).

Use of Limited Water

Water and N are the principal constraints for sustainable crop production in arid region. Response of pearl millet to application of both vary with stage of crop growth. Pearl millet, being mainly a rainfed crop, may be exposed to water deficit any time during growth period. Scarcity of water at certain physiological stages may have higher effect on yield than at other stages. Further, the availability of N may alter the effect of water scarcity as both the factors are known to partly compensate each other (Singh *et al.*, 1976; Singh and Mann, 1979). Studies are therefore, needed for identification of critical crop growth stages where scarcity of moisture is detrimental to yield and mitigating this effect by nitrogen.

Water available for irrigation is limited in arid areas therefore, for increasing crop production it should be used judiciously. In areas, where irrigation is not possible, *in situ* water harvesting is the only way to increase water supply to crop (Mickelson, 1968). Results of some earlier studies on *in situ* water harvesting are therefore also included in this section.

Therefore, experiments were carried out to (i) identify the most critical stage of crop growth influencing yield and nitrogen requirement (ii) determine the optimum requirement of N for pearl millet under different soil moisture availability situations (irrigatged as well as rainfed) (iii) evaluate conjunctive use of rainfall and supplemental water either through irrigation or *in situ* water harvesting for higher pearl millet yield.

Experimental Procedures

A. Effects of Moisture Stress at Different Growth Stages and Nitrogen Levels on Pearl millet Yield

The experiment conducted from 1991-1993 had five water regimes (I_0 to I_4, as detailed in subsequent paragraph) and four levels of nitrogen viz. 0, 40, 80 and 160 kg ha^{-1} and was arranged in randomized block design with three replications. Nitrogen as urea was applied in three splits: sowing, tillering and panicle emergence.

Phosphorus @ 60 kg P_2O_5 ha^{-1} as single superphosphate was applied as basal dose. Pearl millet (cv. MH 179), was sown on July 22, July 25 and July 12 in 1991, 1992 and 1993 after receiving 67.2, 33.5 and 15.5 mm presowing rains, respectively.

In I_1 plots irrigation was given at the termination of vegetative stage (30 DAS) to replenish crop water deficit and subsequent irrigations were given at 50% depletion of ASW from 1 m soil profile. In I_2, adequate water (rainfall + irrigation) was given at early vegetative (up to 30 DAS) and flowering to grain development (50 DAS to physiological maturity). No irrigation was however, given in between 30 to 50 DAS. In I_3, irrigation was withheld at flowering to grain development stage (50 DAS onwards). The rainfall along with irrigation provided 100% replenishment of crop water use in I_4. Rainfed (I_0) served as control. The depth and frequency of irrigation varied with amount and distribution of rainfall in the each season.

B. Effect of Gradient Water and Nitrogen Levels on Pearl millet Yield

Experiment on the effect of life saving supplemental irrigation on productivity of rainfed pearl millet was conducted during 1995 and 1996. Life saving irrigations varying in depths were given by using single line sprinkler systems of irrigation that was kept in the centre of the field. Eight sprinklers were spaced at 6 m distance in 50 x 40 m field to have overlapped water along the line and gradient levels across the line. Six gradients were at 1.5, 4.5, 7.5, 10.5, 13.5 and 16.5 m across the sprinkler line. Irrigation was scheduled whenever the soil moisture depleted to 50% of ASW from 1 m profile in the first water gradient. The zone 15-20 m away from sprinkler line did not recieve supplemental irrigation, and was thus treated as rainfed. Four nitrogen levels viz. 0, 40, 80 and 120 kg ha^{-1} were randomized on both side of sprinklers in each treatment.

C. Effect of *in situ* Water Harvesting and Nitrogen Levels on Pearl millet Yield

This experiment was conducted to study the response of pearl millet to different amount of runoff water and nitrogen levels. Runoff was generated through a 0.5 m wide catchment with 5% slope provided on either side. Catchments were treated in four different way to achieve higher runoff (i) compaction of earth catchment wherein, the soil was compacted to a depth of 10 cm by increasing the density from 1.56 to 2 g cm^{-3} (ii) applying finely grounded pond sediment to a thickness of 12.5 mm on compacted earth catchment and recompacting it with the help of a roller after wetting the top surface (iii) mulching black polyethylene sheet (250 μ) over compacted earth catchment (iv) mixing 2.7 kg of "*Janta emulsion*" (a petroleum product similar to coal tar) with 400 ml kerosene and then spreading it on each meter of compacted surface. Flat surface served as control. Cultivated area of 48 x 2 m in each treatment was divided into four equal plots to apply N @ 0, 40, 80 and 120 kg ha^{-1}. Treatments having four replications were factorially arranged. Pearl millet (cv. BJ 104) was sown on 6 July in 1984 and 1985 and on 25 July in 1986.

Accomplishments

A. Effects of Moisture Stress at Different Growth Stages and Nitrogen Levels on Pearl millet Yield

Growing Season Weather : Pattern of rainfall was different during three years of experimentation (Fig. 1) and therefore duration and extent of moisture stress was also different. Total rainfall during cropping season was similar in 1991 (182 mm) and 1993 (179 mm) but in 1991 one dry spell from 12-28 days after sowing (DAS) and another 44 DAS to crop maturity was observed. The crop experienced two dry spells 15 to 49 DAS and 63 DAS to crop maturity in 1993. In spite of good rainfall (382 mm) in 1992, there were two rain less periods from 25-35 DAS and 50 DAS to crop maturity. Low rainfall combined with high temperature resulted in high evaporation rates in 1991 and 1993. Water use (rainfall + irrigation) varied from year to year depending on rainfall and its distribution (Table 22). Differences in the value of rainfall reported for this experiment with that reported in figure 1 are due to different dates of sowing in this experiment.

Table 22. Total water (rainfall + irrigation), applied in different water regimes during 1991-93.

Year	Water regimes (mm)				
	I_0	I_1	I_2	I_3	I_4
1991	182	392	432	322	472
1992	382	442	442	432	482
1993	179	469	394	404	524
Mean	248	434	423	386	493

Leaf Area Development : Rainfed (I_0) as well as irrigated crop (I_4) attained maximum leaf area index (LAI) at 45 DAS, which declined thereafter (Table 23). Among the treatments irrigated crop showed higher LAI throughout the growth period. The response to N at 45 and 65 DAS was linear in both rainfed and irrigated treatment upto 80 kg N ha^{-1}.

Table 23. Mean leaf area index (LAI) as influenced by N levels in rainfed and I_4 treatment.

N levels ($kg\ ha^{-1}$)	Day 30		Day 45		Day 56	
	I_0	I_4	I_0	I_4	I_0	I_4
0	0.18	0.25	0.86	3.44	0.54	1.46
40	0.30	0.51	1.68	4.96	0.74	1.87
80	0.46	0.68	2.90	6.02	1.20	2.88
160	0.45	0.85	2.87	6.05	1.07	2.56

Grain Yield : The lowest yields were recorded in rainfed crop at all the levels of N (Fig.12, Table 24). The response to nitrogen was quadratic in all the years, however, the differences in yield obtained with application of 40 and 80 kg N ha^{-1} in rainfed crop were not significant in 1991 and 1993. All the irrigated treatments gave significantly higher yield with 80 kg N ha^{-1} than that recorded with 40 kg N ha^{-1} in all the years. Such a trend was observed in rainfed treatment only in 1992, a year of good rainfall.

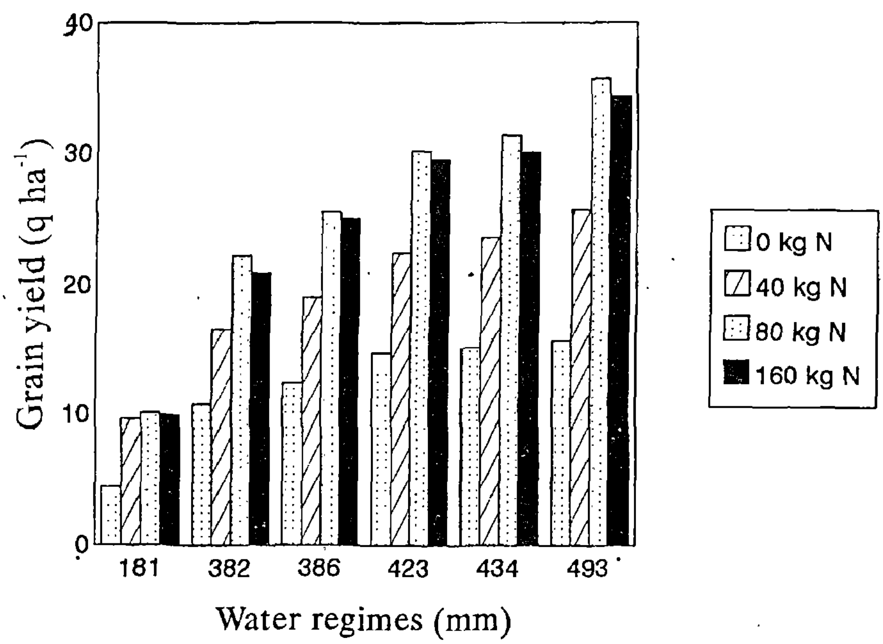

Figure 12. Effect of varying water regimes and four nitrogen levels on pearl millet yield.

Table 24. Grain yield (q ha^{-1}) of pearl millet influenced by irrigation

N levels kg ha^{-1}	Irrigation regimes					
	I_0	I_1	I_2	13	I_4	Mean
1991						
0	4.97	18.69	19.38	11.83	19.58	14.89
40	1.61	24.33	25.44	15.94	27.91	21.05
80	12.16	29.65	31.27	18.07	36.65	25.56
160	12.02	28.46	30.93	17.72	35.02	24.83
Mean	10.19	25.28	26.76	15.89	29.29	
LSD ($p = 0.05$) Irrigation 3.05, N levels 2.15, Irrigation x N 5.15						
1992						
0	10.80	13.70	13.50	13.10	14.00	13.02
40	16.57	22.90	22.70	19.50	24.41	21.22
80	22.75	32.00	31.73	28.90	34.00	29.78
160	20.90	30.43	30.73	28.20	32.50	28.56
Mean	17.62	24.76	24.67	22.42	26.24	
LSD ($p = 0.05$) Irrigation 1.22, N 0.62, Irrigation x N 1.71						
1993						
0	4.09	13.13	11.40	12.32	13.51	10.90
40	7.73	23.66	19.64	21.73	24.98	19.55
80	8.10	32.50	27.60	29.81	36.50	26.90
120	7.93	31.59	27.08	29.23	35.52	26.27
Mean	6.96	25.22	21.43	23.92	27.63	
LSD ($p = 0.05$) Irrigation 1.87, N 1.27, Irrigation x N 3.08						

Moisture stress at flowering to grain development (I_3) stage affected grain yield and maximum reduction (40%) was observed in 1991. About 182 mm rainfall from 43 to 49 DAS in 1992 and 45 mm from 50 to 63 DAS in 1993 alleviated the effects of soil moisture stress to some extent. But in general, the water stress during this stage caused considerable reduction in yield than that recorded at any other stage.

Reduction in yield due to moisture stress at tillering to booting (I_2) was more (16%) in 1993 as the period from 21 to 49 DAS was rainless. Yield reduction was however less during 1991 and 1992 as rainfall was received from 42 to 49 DAS in 1991 and from 35 to 42 DAS in 1992. Yield reductions due to moisture stress at early vegetative stage in the treatment I_1 were less compared to other stages. The magnitude of the reduction was maximum in 1991 due to initial drought. However, about 120 mm rainfall at this stage caused less reduction in yield during 1992 and 1993.

Yield-water-nitrogen Relationship: Since the rainfall was similar in 1991 and 1993, the data of rainfed crop were grouped together but the year 1992 was considered separately being a good rainfall year. However, irrigation treatments were averaged over three years to work out relationship between yield, water and N. The crop gave two kinds of response to N depending upon water supply. Under conditions of low water availability (181 mm rainfall), application of 40 kg N ha^{-1} was optimum (Fig.12). But, under higher water supply conditions (382-493 mm), maximum yield was achieved with 80 kg N ha^{-1}. The physical N optimum, determined from partial derivatives of Y (yield) with respect to N and equating the same to zero ($\delta y/\delta N = 0$), varied with changes in water supply (Table 25). The optima was found to increase steadily with increase in water supply from 181 to 493 mm of water. The highest optimum yield (36.86 q ha^{-1}) was estimated from treatment combining 493 mm of water and 110 kg N ha^{-1}.

Among different irrigation treatments, the lowest regression coefficient was observed in I_3 (Table 25). At this stage water deficit was 22% that caused 20.7% reduction in crop yield compared to I_4 (without N). But application of 80 kg N ha^{-1} decreased the effect of water deficit and the yield level was at par with that obtained in I_4 with 40 kg N ha^{-1}. It provided 51% higher yield than that recorded in I_3 without N. Supplementing 186 mm irrigation (between 30-60 DAS) to seasonal rainfall (248 mm) combined with 80 kg N ha^{-1} provided sustainable production of pearl millet (31.40 q ha^{1}) compared to rainfed (4.53 q ha^{-1}).

Table 25. Mean yield (kg ha^{-1}) to Nitrogen (N) relationship, R^2, optimal N (N opt), optimal yield (Y-opt) and WUE (Kg ha^{-1} mm^{-1})

Water mm	Yield-N-relationship	R^2	N opt	Yopt	WUE
181 (RF)	$4.88+0.1177N-0.00054N^2$	0.78	80	1085	6.0
382 (RF)	$10.92+0.2272N-0.00103N^2$	0.91	95	2385	6.1
386 (I_3)	$12.04+0.2386N-0.00100N^2$	0.91	104	2603	6.7
423 (I_2)	$14.34+0.2795N-0.00116N^2$	0.95	107	3098	7.3
434 (I_1)	$14.77+0.2983N-0.00123N^2$	0.97	108	3264	7.5
493 (I_4)	$15.13+0.3647N-0.00152N^2$	0.97	110	3686	7.5

Water Use Efficiency: Water use efficiency (WUE) was predicted using equation $WUE = Y/I = a/I + b - C/I$, where 'Y' is grain yield in kg ha^{-1}, 'I' is irrigation water in mm and 'a', 'b' and 'c' are the constants of the regression equation between yield and water supply. The WUE increased with increasing water supply (Table 25). Highest WUE 7.5 kg $ha^{-1}mm^{-1}$ was achieved at 434 (I_1) and 493 mm (I_4) of water supply.

Agronomic Nitrogen Use Efficiency: N utilization efficiency (NUE) increased with increasing water upto 493 mm and decreased with each increament of N level (Table 26). Highest NUE under low rainfall situation (181 mm) was recorded with 40 kg N whereas under higher water supply situations (382-493 mm) it was maximum with 80 kg N ha^{-1}.

Table 26. Agronomic nitrogen use efficiency, kg grain kg^{-1} N as affected by applied N and seasonal water supply.

N (kg ha^{-1})	Seasonal water (mm)					
	181[a] (I_0)	382[b] (I_0)	386 (I_3)	423 (I_2)	434 (I_1)	493 (I_4)
40	12.9	14.4	16.6	19.6	21.2	25.2
80	7.0	14.3	16.2	19.3	20.3	25.0
160	3.0	6.3	7.2	9.3	9.4	11.7

[a] low and [b] good rainfall situation

B. Effect of Gradient Water and Nitrogen Levels on Pearl millet Yield

Rainfall received during cropping season in 1994 and 1995 was 528.8 and 302.2 mm, respectively. It was evenly distributed in 1994 but in 1995, only 266 mm was effective as 36 mm water of torrential rains (147 mm) received between 25-27 DAS was lost as runoff or deep percolation. Similarly, in 1996 only 331 mm out of the 421 mm seasonal rainfall was effective.

Grain Yield : Gradient water levels could not be imposed during 1994 due to well distributed rainfall. In 1995 and 1996, gradient water levels were imposed and the data pooled over two years were analyzed to study the response to supplemental irrigation and nitrogen interactions. The effects of gradient water, nitrogen levels and their interactions on the grain yield were significant (Table 27). The grain yield decreased linearly with increasing water deficits at each N level. The highest grain yield (36.40 q ha^{-1}) was recorded with 540 mm water and 80 kg N ha^{-1} and the lowest (6.30 q ha^{-1}) was recorded in rainfed without N. In rainfed condition, 80 kg N ha^{-1} provided 30 and 66% higher yield as compared to 40 kg N ha^{-1} and without N, respectively.

Table 27. Grain yield of pearl millet (q ha^{-1}) as influenced by gradient water and N levels (pooled over 1995 and 1996).

Water gradient (mm)	Nitrogen level (kg ha^{-1}) 0	40	80	160	Mean
540	17.25	25.15	36.40	35.88	28.67
504	15.72	23.30	33.96	33.40	26.60
471	14.38	21.60	31.75	31.15	14.72
410	12.31	19.12	27.65	27.13	21.35
252	8.93	15.67	22.23	21.60	17.13
299	6.30	12.88	18.40	17.95	13.68
Mean	12.48	19.62	18.40	27.86	
LSD (P=0.05)	Water 0.60,	N 0.51,	Water x N 1.25		

Conjunctive use of Seasonal Rainfall with Limited Irrigation : In 1995 effective rainfall was 266 mm, a value close to the average rainfall of the region during cropping season.. Thus, it was considered a representative year. In 1996, effective rainfall was 43 mm higher than the average and therefore, was considered a better rainfall year. From gradient irrigation treatments (Table 28), rainfed, low and moderate and potential irrigation levels were selected for average and good rainfall situation.

Table 28. Pearl millet yield under rainfed conditions and with supplemental irrigation during 1995 and 1996.

Irrigation regime	Water used from supplemental irrigation (mm)	Grain yield (q ha^{-1})	WUE (kg ha^{-1} mm^{-1})
1995			
Rainfed	0	14.00	-
Low	73	18.90	6.71
Moderate	145	26.70	8.76
Potential	292	36.30	7.64
1996			
Rainfed	0	22.8	-
Low	39	25.6	7.18
Moderate	76	28.6	7.63
Potential	190	36.6	7.26

1995 (266 mm) - a year of average rainfall
1996 (331 mm) - a year of above average rainfall

The yield obtained with potential irrigation (190 and 292 mm) was higher than that recorded under rainfed conditions. WUE changed with level of irrigation and highest was obtained with moderate supplemental irrigation.

C. Effect of *in situ* Water Harvesting and Nitrogen Levels on Pearl millet

Runoff Efficiency : In the first year, catchment covered with polyethylene sheet recorded a 100% runoff as the threshold value was negligible (Table 29). It was followed by Janta emulsion, pond sediments and compacted earth catchment in that order. But in second year threshold retention for four surface sealing materials ranged between 0.71 to 3.09 mm. The decline in runoff efficiency and increase in threshold retention in second year could be attirbuted to shrinkage in polyethylene surface due to temperature variations and solar radiations (Singh and Singh, 1997). Development of cracks and subsequent erosion in other catchments may be responsible for increased water retention. Sealing of catchments increased the water supply from 41 mm in compacted earth catchment to 69 mm in polyethylene covered catchment (Table 29). The coefficients of correlation between precipitation (P) and runoff (Q) approached unity (0.98 to 0.99) reflecting high efficiencies of catchments.

Table 29. Relationship between rainfall (P) and runoff (Q) in different treatments

Treatments	Regression equations	Correlation coefficients	% Runoff efficiency	Threshold retention
1985				
Polyethylene	Q=0.9936P-0.0614	0.999**	99.4	0.06
Janta emulsion	Q=0.9852P-0.2819	0.999**	98.5	0.29
Pond sediment	Q=0.8999P-1.7834	0.999**	90.0	1.98
Compacted earth	Q=0.6842P-0.8431	0.996**	68.4	1.23
1986				
Polyethylene	Q=0.9207P+0.772	0.995**	92.0	0.76
Janta emulsion	Q=0.8342P-0.5896	0.994**	83.4	0.71
Pond sediment	Q=0.8779P-2.7104	0.988**	87.8	3.09
Compacted earth	Q=0.6327P-1.7415	0.998**	63.3	2.75

Grain Yield : The increased water supply, acted as supplemental irrigation, enhanced the yield from 4.00 q ha^{-1} in flat surface to 12.40

q ha^{-1} in polyethylene covered catchment at 80 kg N ha^{-1} (Table 30). Crop receiving 80 kg N ha^{-1} and catchment mulched with polyethylene recorded highest yield followed by that recorded in catchment coated with *Janta* emulsion. In other treatments, by and large N at 40 kg ha^{-1} was better. The WUE increased with increasing water supply combined with 80 kg N ha^{-1}, from 4.9 (compacted earth) to 12.2 kg ha^{-1} mm^{-1} water (polyethylene covered catchments).

Table 30. Effect of different treatments on water supply (mm), grain yield of pearl millet

Treatments	D (mm)	N (kg ha^{-1}) 0	40	80	120	Added water (mm)	Added WUE at 80kg N (kg ha^{-1} mm^{-1})
Flat surface	143	1.78^{a*}	3.98^{a}	4.00^{c}	$3.66^{b,c}$	0	—
Polyethylene	212	$6.17^{f,g}$	8.36^{j}	12.40^{k}	8.46^{j}	69	12.2
Janta emulsion	202	4.57^{d}	6.86^{h}	7.78^{i}	7.44^{i}	59	6.4
Pond sediment	198	4.00^{c}	$6.55^{g,h}$	6.80^{h}	5.60^{e}	55	5.1
Compacted earth	184	3.37^{b}	$5.85^{e,f}$	$6.00^{e,f}$	4.63^{d}	41	4.9

D = P - Q.Am/AC where D - depth of water supply from rain + runoff, P - precipitation, Q - Runoff, Am-catchment area and Ac - crop area

Different superscripts denote significantly different values

Discussion

Our studies demonstrated that water stress at flowering to grain development was more detrimental to crop growth and yield than the one at early stages. These findings are in line with the observations of other workers from similar agroclimatic conditions (Bidinger *et al.*, 1987; Seetha Rama *et al.*, 1982).

In the present study maximum LAI was recorded after 45 DAS both under rainfed (I_0) as well as irrigated conditions and its decline thereafter have also been reported by Singh and Singh (1997). Higher LAI reduced evaporation losses from soil surface, and conserved moisture that was used for transpiration by better conopy cover of the crop. Low grain yields of the rainfed crop during 1991 and 1993 may be attributed to small LAI (Ritchi and Burnett, 1979) whereas reverse was true for higher yield during 1992.

Occurrence of rain after initial drought favor faster growth thus the crop achieved peak LAI shortly thereafter (Bidinger *et al.*, 1987; Mahalakshmi *et al.*, 1985; and Singh and Singh, 1997). In our experiment also, supplemental irrigation after 30 DAS in treatment I_1

helped in better regeneration and stress hardening in early vegetative stage. Such crop would be better adapted to withstand water stress at later stages and may ultimately produce higher yield (Bidinger *et al.*, 1987).

The low regression coefficients calculated for rainfed compared to any other treatment indicated that grain yield was most affected with moisture stress (Table 25). It further showed that, flowering to grain development stage (I_3 treatment) was most sensitive to water stress compared to any other stage. Water deficit effects were partly compansated by addition of N particularly at 80 kg ha^{-1}.

A linear increase in WUE with increasing water supply observed in the present study has also been recorded for pearl millet (Squire *et al.*, 1986) and sorghum (Steiner, 1987). It is however apparent that considerable improvements in crop yield are not possible without supplemental irrigation. Thus, it would be apt to add around 190 mm of water to seasonal rainfall (248 mm) at 30-60 DAS along with 80 kg N ha^{-1} to achieve high grain yield and WUE.

N utilization efficiency increased with increased water supply, as water promoted plant growth and increased N demand. Comparatively higher NUE at 40 kg than with 80 kg N ha^{-1} under low water supply and equal NUE at higher water supply suggested better utilization of N use by increased water supply. Thus our study suggest that in low rainfall years, 40 kg N ha^{-1} is the optimum level of N in rainfed areas. On the other hand, where limited irrigation is available supplementing a little water combined with 80 kg N ha^{-1} at active vegetative or flowering stage considerably improved the yield over rainfed crop. These options can be used for sustaining pearl millet yield in arid region.

Higher WUE recorded with moderate levels of water supply in spite of highest yield with potential irrigation was in contrast to the observations of Stewart (1989) and Singh (1995). A situation of achieving highest yield with irrigation water may not be advantageous in a region where irrigation water is limited but size of land holdings is large. This logic is primarily borne out of the fact that high water losses are observed in the event of frequent and heavy irrigations on the one hand and a need to keep losses at minimum in water scarce areas on the other. Hence, in such areas emphasis should be given to maximize production per unit of added water. Water simulations (Table 31) have indicated that if a crop is provided with light irrigation in addition to water received through rainfall, then it would result in saving of considerable water. Water thus saved can be used for supplemental irrigation in additional area for increasing total production from a land holding though crop yield per unit land would be low. However, the depth and timing of irrigation is governed by amount and distribution of rainfall as well as crop growth stages. Flowering to grain development is the most critical stage for determining the yield of pearl millet. Incidently, probability of rainfall in the region is relatively low at this stage (Singh *et al.*, 1995). In situations, where water is available only for one irrigation, it should be given at flowering to grain development stage. However, under late sown conditions (2nd fortnight of July), this irrigation may be scheduled towards the end of vegetative stage when the probability of rainfall is extremely low.

Table 31. Increased area under given water supply enhanced the pearl millet production.

Supplemental	Water saved (mm)	Additional area (ha)	Production (q)
1995			
266 mm (average rainfall) Given water supply 292 mm			
73	219	4	75.60
145	147	2	53.40
292	0	1	36.30
1996			
331 mm above average rainfall Given water supply 190 mm			
39	151	4.9	125.44
76	114	2.5	71.50
190	0	1.0	36.60

Our studies on moisture conservation suggest that in the areas where irrigation is not available, *in situ* water harvesting is an appropriate way to enhance the total water supply available and increasing yield. Increase in threshold retention of different sealing materials from second year onwards may be due to weathering of sealing materials. Therefore, for achieving better runoff, rennovation of catchments with sealing material is required once in three years.

Conclusions

The crop productivity levels in rainfed agriculture of arid regions are not only low but variable too and poor fertility status of soils and recurring droughts leading to moisture deficiency at critical stages of crop growth are the major causes for this. The research activities conducted so far, for enhancing the productivity from rainfed agriculture have mostly revolved around the use of fertilizers. This is not sustainable strategy looking into the risk factors involved with agriculture in this region. Therefore, for sustainable rainfed agriculture in arid regions, efficient utilization and conservation of natural resources assumes importance. An integrated approach involving the aspects of soil, crop and water management was adopted and studies were conducted for more than a decade to evolve low input technologies for higher production based on efficient use of natural resources like crop sequences, crop residues and scarce water. The main findings are briefed as below which would be relevant for attaining the sustainability in dryland agriculture.

Crop sequence involving a legume in the system plays an important role in restoring the soil fertility with respect to nitrogen and other biological parameters thus contributing to long-term sustainability of the soil. However, the type and duration of a legume determines to a great extent the advantage accrued to the system. In the arid region, three legumes viz. clusterbean, mung bean and moth bean are extensively grown. Our studies have revealed that clusterbean is the most effective crop for improving soil quality with respect to organic-C, N, microbial biomass and soil enzymes. This improvement in soil environment also helps the crop in mitigating the adverse effect of early drought besides improving the utilization efficiencies of fertilizer-N. The long term studies have shown that continued cultivation of pearl millet deplete the fertility of soil, leading to decline in grain and biomass yield with time but adopting a sequence of clusterbean-clusterbean-pearlmillet in the same piece of land, is more remunerative not only in economic terms but also for improving soil quality and enhancing N use efficiency. The beneficial effects of clusterbean are attributed to the addition of leaves equivalent to 10 - 12 kg N ha^{-1} through natural shedding besides enriching soil organic N pool with hydrolyzable NH_4-N, an important source of N to pearl millet.

For the N and organic-C starved soils, addition of crop residues, animal manure and compost offer an alternative but sustainable system by enriching soils with these nutrients. However, their proper management in conjunction with fertilizer nitrogen can make the system more productive. The studies have shown that the C:N ratio of crop residues and decomposition rate determine the effectiveness of their addition. The residues of legume crop particularly clusterbean having low C:N ratio (64:1) and rapid rate of decomposition have been found to be more effective over those of pearl millet with wide C:N ratio (80:1). Surface incorporation of crop residues of clusterbean @ 2 t ha^{-1} or N-equivalent of 20 kg N ha^{-1}, results in soil moisture conservation, enhances nitrogen use efficiency by 50 - 60% and pearl millet yield by 70 - 80%. Clusterbean residues in conjunction with 40 kg fertilizer N ha^{-1} has been found to be an optimum combination for soil quality improvement and achieving sustainable yield of pearl millet in the region.

Dry root rot disease caused by the pathogen *Macrophomina phaseolina* is a major reason of low clusterbean yield in the region. Earlier studies have shown that the propagules of this pathogen remain dormant during hot summer months of May and June and their activity is dependent on organic matter level and moisture conditions.For the first time, the studies were initiated on the possible use of crop residues and their management with soil moisture manipulation for the control of this pathogen. Successful results were obtained by incorporating cruciferous residues (@ 5 t ha^{-1}) of mustard and cauliflower during May or early June followed by one irrigation.This practice could decrease the infection sustainedly and enhanced the productivity of clusterbean in kharif season. At times, incorporation of crop residues may add *Macrophomina phaseolina* propagules in soil. Attempts were therefore made to inactivate these propagules by preparing compost of crop residue. Amending compost in soil not only reduced root rot mortality but also induced suppressiveness in soil.

In rainfed agriculture moisture availability at critical growth stages is the main determinant factor of crop yield. Distribution of rainfall during cropping season plays a crucial role to determine the N-yield relationship compared to total quantity of rainfall received. The studies have revealed that among different crop growth stages, moisture stress at 50 DAS to physiological maturity was most crucial for yield reduction. The N-moisture-yield relationship models developed for critical stages of growth, have opened up the possibility of management of available irrigation water and fertilizer-N to mitigate the drought effects for yield stability and efficient use of scarce resources.

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