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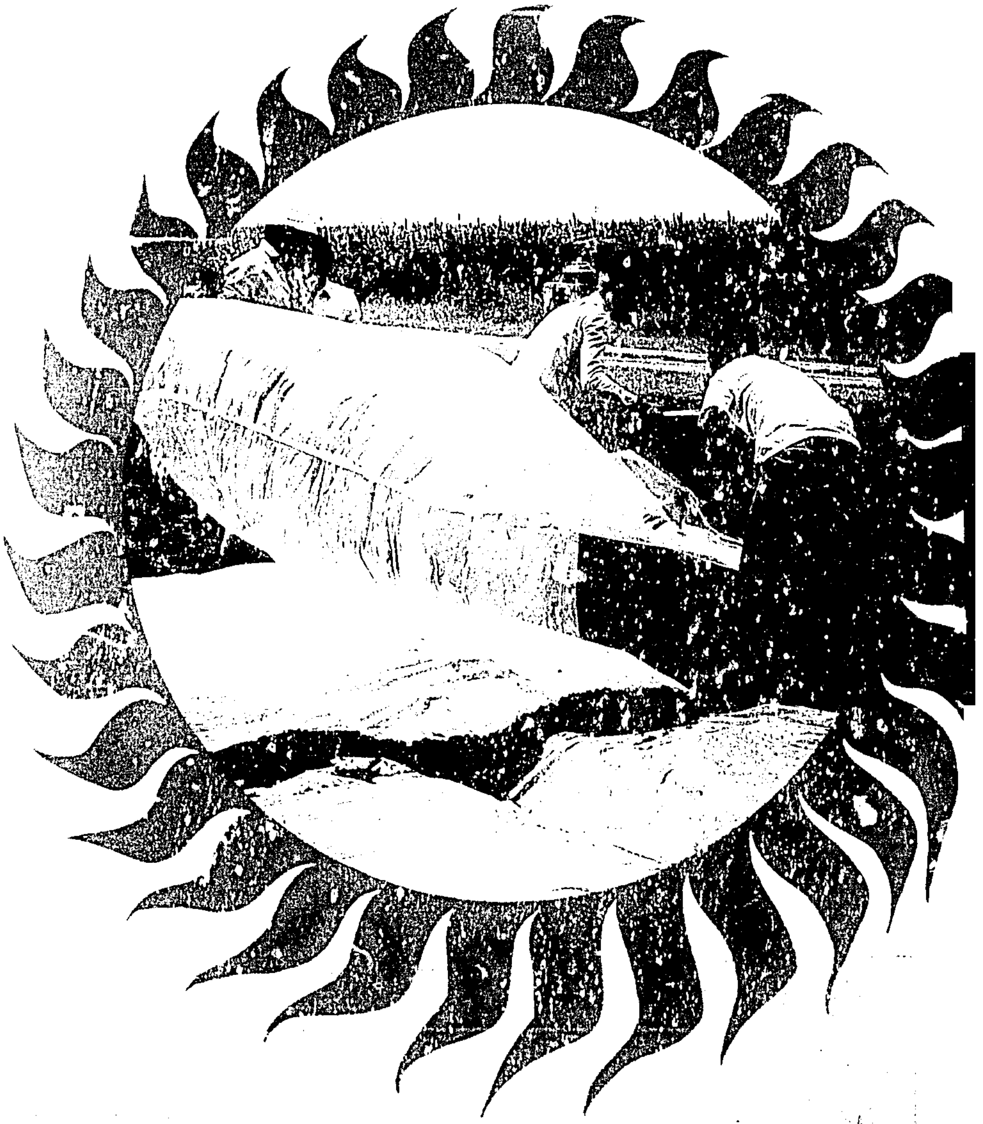

# Effects of Soil Solarization on Pigeonpea and Chickpea

Research Bulletin no. 11

## Abstract

Chauhan, Y.S., Nene, Y.L., Johansen, C., Haware, M.P., Saxena, N.P., Sardar Singh, Sharma, S.B., Sahrawat, K.L., Burford, J.R., Rupela, O.P., Kumar Rao, J.V.D.K., and Sithanantham, S. 1988. **Effects of Soil Solarization on Pigeonpea and Chickpea.** Research Bulletin no. 11. Patancheru, A.P. 502 324, India: International Crops Research Institute for the Semi-Arid Tropics.

The experience gained with field tests on the effects of soil solarization on pigeonpea (*Cajanus cajan* (L.) Millsp.) and chickpea (*Cicer arietinum* L.) crops through a multidisciplinary team effort, at ICRISAT Center during 1984-87, is highlighted. The studies were conducted in fields infested with fusarium wilt. Solarization was done by covering the soil with transparent polythene sheeting (100 μm thick) for 6-8 weeks during summer (April-May). This increased soil temperatures by 6-10°C in the 0-20-cm soil profile. Other changes recorded were increased mineralization of soil nitrogen to nitrate, a decline in populations of fusarium propagules and plant parasitic nematodes, and decreased weed infestation. When the crops were grown, effective control of fusarium wilt disease in the susceptible genotypes of pigeonpea and chickpea was observed along with improved plant growth and yield. Nodulation and N-fixation were adversely affected because of the decline in *Rhizobium* population with solarization. However, plant growth and yield were not adversely affected probably because of the compensatory effect of increased soil nitrate. Even in wilt-resistant genotypes of both crops, particularly of pigeonpea, there was a significant increase in yield indicating beneficial effects of solarization other than disease control. There was a considerable residual effect of solarization in the second and third seasons on yield of chickpea, but not of pigeonpea. Different techniques and methods employed in applying solarization and in assessing its impact are described. The implications of utilizing solarization for these and other crops are discussed.



## Résumé

Chauhan, Y.S., Nene, Y.L., Johansen, C., Haware, M.P., Saxena, N.P., Sardar Singh, Sharma, S.B., Sahrawat, K.L., Burford, J.R., Rupela, O.P., Kumar Rao, J.V.D.K. et Sithanantham, S. 1988. **Effets de la solarisation du sol sur le pois d'Angole et le pois chiche.** Bulletin de recherche n° 11. Patancheru, A.P. 502324, Inde : International Crops Research Institute for the Semi-Arid Tropics.

Les faits saillants de l'expérience acquise dans les essais en champs sur les effets de la solarisation du sol sur le pois d'Angole (*Cajanus cajan* (L.) Millsp.) et le pois chiche (*Cicer arietinum* L.) au Centre ICRISAT au cours des années 1984-87 sont présentés. Ces essais ont été conduits par une équipe multidisciplinaire dans les champs infestés par la fusariose. La solarisation a été effectuée en recouvrant le sol d'un film de polyéthylène transparent (100μm d'épaisseur) pendant 6-8 semaines en été (avril/mai). Cette technique a élevé la température de 6-10°C dans le profil 0-20 cm du sol. D'autres résultats ont été la minéralisation accrue de l'azote du sol au nitrate ainsi qu'une baisse des propagules de *Fusarium*, des nématodes et des mauvaises herbes. Une maîtrise efficace de la fusariose chez les génotypes sensibles de pois d'Angole et de pois chiche ainsi qu'une amélioration de la croissance et du rendement des cultures ont été signalées. La nodulation et la fixation de l'azote ont été affectées à cause de la réduction de la population de *Rhizobium* avec la solarisation. Cependant, il n'y a pas eu d'incidence négative sur la croissance et le rendement, peut-être grâce à l'effet du nitrate élevé du sol. Même chez les génotypes résistants à la fusariose des deux cultures, en particulier de pois d'Angole, il y a eu une augmentation significative du rendement, ce qui indique des effets positifs de la solarisation, différents de ceux responsables pour la maîtrise des maladies. La solarisation a eu un effet résiduel sensible dans les deuxième et troisième campagnes sur le rendement du pois chiche mais non pas sur sur celui du pois d'Angole. Diverses techniques utilisées dans l'application de la solarisation et dans l'évaluation de son effet sont décrites. La portée de l'emploi de la solarisation pour ces légumineuses et d'autres cultures est discutée.


**Cover:** *In the foreground is a pigeonpea crop grown on nonsolarized soil and in the background the one benefiting from residual effects of solarization; and* (within sun diagram) *transparent polythene sheeting being laid for solarization treatment of the field.*

# Effects of Soil Solarization on Pigeonpea and Chickpea

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# Introduction

Soil solarization is a method of heating soil by covering it with transparent polythene sheeting during hot periods to control soilborne diseases. The effects, advantages, and limitations of this technique have been recently reviewed by Katan (1981) and Horiuchi (1984). The technique has been commercially exploited for growing high-value crops in diseased soils in environments with a hot summer (maximum daily air temperatures regularly exceeding 35°C). Examples include control of verticillium and fusarium diseases in vegetable crops in Israel and control of *Verticillium dahliae* in pistachio orchards in California, USA (Katan 1981, 1984).

Although the major benefit of solarization is reduction of soilborne pathogens by soil-heating effects, there are many other possible additional beneficial effects that can result in an increased growth response (IGR) of plants. Such additional effects include control of weeds and insect pests and release of plant nutrients (Katan 1981; Horiuchi 1984).

It has been pointed out (J. Katan, Plant Pathology, Hebrew University, Jerusalem, Israel, personal communication, 1985) that farmers of the Deccan plateau in India have long exploited a form of solar heating of soil, by plowing the soil so as to expose subsoil prior to the hot summer period (April-June), when maximum daily air temperatures usually exceed 40°C, and leaving it fallow. We were interested to determine whether this solar-heating process in this region could be enhanced by mulching with polythene sheeting, particularly for controlling the fusarium wilts of pigeonpea (*Cajanus cajan* (L.) Millsp.) and chickpea (*Cicer arietinum* L.), which are major limitations to growth of these crops in the Indian subcontinent.

We realized that widespread use of soil solarization enhanced by plastic mulching for such extensively grown, low-input crops was not likely to be economical. However, the technique could be of potential use on research stations, where it is necessary to repeatedly grow chickpea and pigeonpea on the same land, and for commercial seed production, where it is necessary to minimize seed transmission of soilborne pathogens. Further, the experience described herein may be useful for researchers working on crops with high value per unit land area, which are grown in peninsular India and similar environments in South Asia.

A multidisciplinary team of scientists at ICRISAT Center examined various effects of solarization on pigeonpea and chickpea. Experiments were conducted over 3 consecutive years to determine repeatability of the results. In this bulletin, we summarize methodologies employed and the results obtained in these studies. Suggestions have been made for the future use of solarization in comparable semi-arid tropical environments.

# Materials and Methods

## Experimental site

Experiments with pigeonpea and chickpea were conducted on fusarium-wilt-sick fields at ICRISAT Center (17°N 78°E, 545 m elevation) during the 1984/85, 1985/86 and 1986/87 seasons. All experiments were done on Vertisol (Typic Pellusterts) fields (BIL 2B, BIL 2C, and BM 9A), apart from one in 1986/87 with pigeonpea on an Alfisol (Udic Rhodustalfs) field (RM 8E). On each field, except BM 9A, soil inocula of *Fusarium udum* for pigeonpea, and *F. oxysporum* f.sp *ciceri* for chickpea, had been previously enhanced by intensive and repeated incorporation of wilt-infected plant material to create uniformly wilt-sick plots to screen for resistance. Field BM 9A had become wilt sick due to repeated growing of chickpea crops with wilt-susceptible genotypes.

Chemical characteristics of the soil of each field at the beginning of the experiment are given in Table 1. No fertilizer was applied in any field, except 40 kg ha$^{-1}$ of zinc sulfate to BIL 2C in 1985/86. The fields were cultivated and prepared into 1.5 m-wide broadbeds and furrows.

## Experimental layout

In 1984/85, split-plot experiments were conducted for pigeonpea in field BIL 2B and chickpea in field BIL 2C. Main plots comprised those with presence and absence of irrigation prior to solarization and subplots were a factorial combination of a wilt-susceptible genotype (pigeonpea - LRG 30, chickpea - ICCV 1) and a wilt-resistant genotype (pigeonpea - ICP 8863, chickpea - JG 74) with and without solarization. There were six replications.

In 1985/86, the above experiment was repeated (subsequently referred to as "repeat study") for pigeonpea on an adjacent wilt-sick area in BIL 2B, but there were only four replications. In 1986/87, solarization experiments were also

**Table 1. Chemical characteristics of soils of solarization experiments on chickpea and pigeonpea at the beginning of experimentation, ICRISAT Center, 1984/85 (BIL 2B, BIL 2C) and 1986/87 (BM 9A, RM 8E).**

| Chemical characteristic | BIL 2B Vertisol (0-45 cm) Pigeonpea (n = 72) | BIL 2C Vertisol (0-45 cm) Chickpea (n = 72) | BM 9A Vertisol (0-60 cm) Chickpea (n = 32) | RM 8E Alfisol (0-45 cm) Pigeonpea (n = 48) |
|---|---|---|---|---|
| pH | 8.4 | 8.3 | 8.5 | 8.3 |
| Electrical conductivity (dSm$^{-1}$) | 0.18 | 0.20 | 0.34 | 0.21 |
| Available P (mg kg$^{-1}$) | 2.9 | 3.9 | 7.4 | 27.3 |
| $NH_4$-N (mg kg$^{-1}$) | 37.9 | 12.01 | 11.2 | 7.1 |
| $NO_3$-N (mg kg$^{-1}$) | 12.8 | 7.0 | 42.0 | 8.2 |

conducted in RM 8E for pigeonpea and in BM 9A for chickpea. There were four replications of the factorial combination of wilt-resistant and wilt-susceptible genotypes with and without solarization. These experiments were laid out in a Latin Square and irrigated prior to solarization.

The 1984-85 experiments were continued in 1985-86 by dividing them into three blocks each and imposing solarization treatments on each of the 1st year's subplot treatments. In 1986-87, the irrigation treatments were discontinued and only plots that had been solarized in each of the previous two seasons were solarized again to provide a control for measuring residual effects of solarization given in either 1984 or 1985. Thus, in this season, there were six replications.

Plot size (or subplot size for split-plot arrangement) in experiments in BIL 2B and BIL 2C was 6 m × 6 m (four broad beds) and 6 m × 5 m at the other sites. A 3 m-wide buffer zone was maintained between plots. Clear polythene sheeting of 400 gauge (94 g m$^{-2}$ and 100 μm thick) and 6-m wide was laid on the appropriate plots 2-3 days after irrigation of the main plots (Fig. 1). Soil was placed around the edges of each polythene sheet to secure it.

Details of duration of solarization treatments, sowing and harvest dates, irrigation applied during the cropping season, rainfall, sunshine hours, and total radiation are given in Table 2.

Interrow spacing was 75 cm for pigeonpea and 30 cm for chickpea. Within-row spacing for pigeonpea was 30 cm in 1984-85 and 15 cm thereafter. It was 10 cm for chickpea in each season.

## Soil moisture

Soil-moisture content was measured gravimetrically in 0-5, 5-15, 15-25, and 25-40 cm depths before and after solarization in the fields BIL 2B and BIL 2C during 1984-85 and 1985-86.

**Figure 1. Layout of polythene-covered plots in a solarization experiment.**

Presolarization sampling was done 24 h after irrigation followed by the postsolarization sampling soon after removing the polythene sheeting.

## Soil temperature

Soil temperatures (°C) were monitored in two replications in BIL 2B in 1984-85 and 1985-86 using copper-constantan thermocouples buried at 5, 10, 20 cm depths. Temperature measurements were made at 0300, 0600, 0900, 1200, 1500, 1800, and 2400, which were automatically logged into a Campbell Scien-

**Table 2. Dates of solarization treatments, sowing and harvest, and irrigation application in solarization experiments; sunshine hours, solar radiation, and rainfall during the crop growth period, ICRISAT Center, 1984-87.**

| | BIL 2B, Pigeonpea | | | BIL 2C, Chickpea | | | BM 9A Chickpea | RM 8E Pigeonpea |
|---|---|---|---|---|---|---|---|---|
| Operation factor | 1984-85 | 1985-86 | 1986-87 | 1984-85 | 1985-86 | 1986-87 | 1986-87 | 1986-87 |
| Solarization begun | 13 Apr | 26 Apr | 16 Apr | 17 Apr | 22 Apr | 16 Apr | 22 Apr | 21 Apr |
| Solarization terminated | 4 Jun | 6 Jun | 2 Jun | 4 Jun | 6 Jun | 2 Jun | 4 Jun | 4 Jun |
| Sowing date | 25 Jun | 25 Jun | 25 Jun | 2 Nov | 17 Oct | 14 Oct | 15 Oct | 25 Jun |
| Harvest time | 21 Jan-6 Feb | 31 Dec-23 Jan | 12 Jan | 18 Feb | 4-10 Feb | 11 Feb | 9 Feb | 12 Jan |
| Irrigation applied[1] | | | | | | | | |
| Before solarization | 12 Apr | 24 Apr | 12 Apr | 16 Apr | 19 Apr | 11 Apr | 15 Apr | 17 Apr |
| During crop growth | 1 Jun | - | - | 3 Nov | - | 16 Oct | 16 Oct<br>12 Nov<br>17 Dec | 11 Jul<br>5 Sep<br>15 Oct<br>4 Nov |
| Cumulative sunshine (h) | 510 | 369 | 465 | 470 | 400 | 465 | 417 | 422 |
| Total solar radiation (MJ m$^{-2}$ day$^{-1}$) | 1180 | 914 | 1081 | 1090 | 999 | 1081 | 989 | 1008 |
| Rainfall (mm) | 511 | 384 | 475 | 89 | 154 | 48 | 48 | 475 |

1. About 50 mm irrigation was applied each time.

tific's CR 5 data-logging device. Air temperatures at 50-cm height from the soil surface hours were simultaneously logged.

## Chemical analysis

Soil samples were collected from each experimental plot before and after solarization. Composite samples of four cores per plot were taken at soil depths of 0-15 cm, 15-30 cm, and 30-45 cm.

The soil samples were air-dried and passed through a 2-mm seive before analysis. Soil pH and electrical conductivity (EC) were measured in a soil suspension using a soil to water ratio of 1:2. Available P was measured after extraction with 0.5 M $NaHCO_3$ as described by Olsen and Dean (1965). Ammonium-N and nitrate-N were measured in 2 N KCl extracts by steam distillation with MgO and Devarda's alloy (Bremner 1965).

## Weed growth

Plots were hand weeded prior to sowing and whenever weeds grew big enough to compete with pigeonpea. Weeds removed from the pigeonpea experiments in BIL 2B in 1984/85 and 1985/86 were identified and their dry mass recorded. Weeds were allowed to grow on the chickpea plots after the solarization, but were killed by a paraquat spray (@ 1 L a.i. ha$^{-1}$) applied prior to sowing. During chickpea growth, plots were cleared of weeds by hand weeding.

## Soil insects and other arthropods

Emergence cages (150-cm long × 50-cm wide × 15-cm high) were installed in the pigeonpea genotype ICPL 30 plots in BIL 2B soon after solarization was completed to trap soil-dwelling insects, such as the pigeonpea nodule fly, *Rivellia angulata*. In the 1985/86 season, the emergence of the adults into these cages was monitored from 13 June until early August. Soil samples to a depth of 15 cm were taken at five places in each plot to see if any soil-inhabiting arthropod fauna, such as termites and ants, were influenced by the solarization treatment during 1985/86. The pooled soil from each plot (400–500 g) was kept in a Berlese Extraction Apparatus for 3 days to extract any living arthropods. The sampling commenced on 10 June and was repeated at weekly intervals until 5 July.

## Nematodes

To assess nematode populations, six soil cores to 20 cm depth were bulked for each plot. Populations were determined in 200 mL aliquots using the Cobb decanting and sieving technique (Cobb 1918) followed by the modified Baermann Funnel technique (Schindler 1961). *Heterodera cajani* cysts in pigeonpea plots were collected on an 80-mesh (pore size = 180 μm) sieve. In chickpea plots, nematode populations were assessed before and after solarization, just before chickpea sowing and at crop maturity.

## *Fusarium*

Soil samples were collected to estimate the number of *Fusarium* propagules before and after solarization and at maturity of the crops. In chickpea, soil samples were also collected at the time of sowing in October. From each plot, five cores of soil to a depth of 15 cm were sampled and the cores bulked and air-dried. After grinding and sieving, 10-g subsamples of soil were used to estimate *Fusarium* propagule numbers.

Selective media were used to estimate *Fusarium* populations in the soil. The populations of *Fusarium oxysporum* f.sp *ciceri* were estimated on modified Czapek-Dox agar, which contained, in addition to normal ingredients, 500 mg pentachloronitrobenzene, 25 mg malachite green, 750 mg Dicrysticin-S, and 2 g yeast extract per L of medium (Singh and Chaube 1970). Populations of *F. udum* (pigeonpea wilt pathogen) were estimated on Nash and Snyder's (1962) medium. The basal medium was adjusted to pH 5, autoclaved, and then 750 mg of Dicrysticin-S added to the medium. The medium was dried in petri dishes for 3 days before use.

Soil samples of 100 mg were evenly spread on the surface of the medium in sterilized petri plates. For each sample, there were three plates. Petri plates were incubated at 25°C for 5 days, and the number of *Fusarium* colonies counted and calculated per gram of soil.

Plants in these experiments were monitored throughout the growth period for disease symptoms caused by *Fusarium* spp.

## *Rhizobium*

To estimate pigeonpea and chickpea rhizobial populations, composite soil samples were collected from the top 15 cm of soil in solarized and nonsolarized plots and most probable number (MPN) counts of chickpea and pigeonpea rhizobia determined (Kumar Rao and Dart 1981; Toomsan et al. 1984). Nodule number and mass were recorded from 5/6-week-old pigeonpea and chickpea plants after careful excavation of roots.

## Plant growth and yield

Plant height of pigeonpea was regularly recorded. For both crops the following parameters were recorded: phenology, plant stand, seed yield, total above-ground dry matter at maturity, pods plant$^{-1}$, number of seeds pod$^{-1}$, and 100-seed mass. The sampling area for seed yield and plant dry matter for each plot at maturity was about 15 m$^2$.

# Results

## Soil moisture

Trends in soil moisture measurements in the 1984/85 and the 1985/86 seasons were similar. Thus results for only 1984/85 are presented.

An irrigation of about 50 mm just before solarization increased soil moisture content to near field capacity of Vertisol (30%, weight/weight). As water was uniformly applied, the water-content profiles in the irrigated solarized and the irrigated nonsolarized treatments were identical in the beginning (Fig. 2a). After placement of polythene sheeting on the plots, prolific condensation of moisture on the inner surface of the polythene sheeting in the irrigated treatment helped the sheeting to adhere to the soil surface. In the nonirrigated treatment, condensation was lesser than the irrigation treatment, making the sheeting more vulnerable to wind, leading to tearing of the sheeting. After the termination of solarization, the irrigated solarized treatment had lost much moisture to a depth of 25 cm (Fig. 2b) through evaporation and resultant condensation under the sheeting. Below a depth of about 25 cm, the water-content profile was similar to that before solarization. In the irrigated nonsolarized treatment, as there was no polythene sheeting to conserve moisture, moisture loss was such that the water profile resembled the nonirrigated treatments at the end of solarization (Fig. 2b). To reduce the differences in soil moisture among plots prior to sowing of pigeonpea, an irrigation (about 50 mm) was given at sowing in 1984/85. In the following season, sowing was done after sufficient rainfall had charged the soil profile with moisture.

## Soil temperature

The maximum temperatures at various depths of soil were reached daily at 1500 and hence temperatures measured at this time only are given in Table 3. The plots covered with polythene sheeting had markedly higher maximum temperatures at all depths at which temperature measurements were made. At 5 cm, solarization increased temperature by about 10°C. The range of temperature increases with solarization and was less in the surface layers (5 cm and 10 cm) of irrigated plots as compared to the nonirrigated plots. This was probably due to the heat required by the water to evaporate, which was subsequently transferred to the polythene sheeting as indicated by the condensation of water on the lower surface of sheeting. The temperatures higher than 40°C and 45°C, which could be lethal for microorganisms, were recorded for most of the duration of solarization at 5 cm and 10 cm depths. In the nonsolarized treatment, such high-temperature days were fewer.

## Chemical properties of the soil

Solarization did not significantly affect pH, EC, or available P levels. Soil $NO_3$-N concentration was increased, specially where

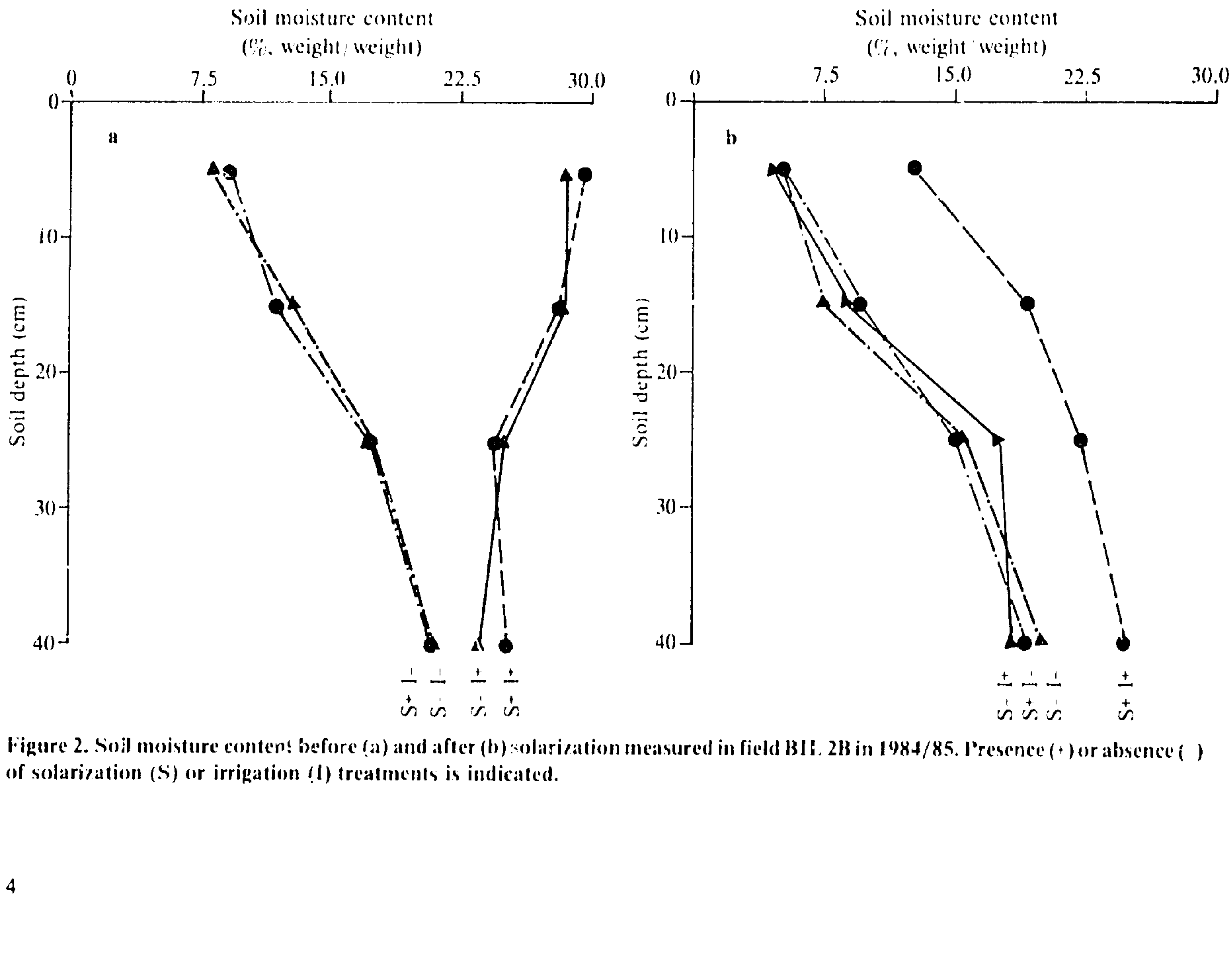


**Figure 2. Soil moisture content before (a) and after (b) solarization measured in field BIL 2B in 1984/85. Presence (+) or absence (-) of solarization (S) or irrigation (I) treatments is indicated.**

**Table 3. Effects of solarization (S) and irrigation (I) treatments on maximum soil temperatures recorded at 1500 in BIL 2B. Corresponding air temperatures recorded at 50 cm from bare soil surface are also given, ICRISAT Center, 1984/85.**

| Treatment[1] | Soil depth (cm) | Temperature (°C) Range | Mean over solarization period | Number of days >40 °C | >45 °C |
|---|---|---|---|---|---|
| S+ I+ | 5 | 39.0-54.1 | 49.9 | 50 | 48 |
| S- I+ | 5 | 34.7-44.6 | 40.5 | 30 | 0 |
| S+ I- | 5 | 41.3-60.7 | 53.9 | 51 | 49 |
| S- I- | 5 | 35.3-47.7 | 43.7 | 46 | 22 |
| S+ I+ | 10 | 38.4-48.0 | 44.4 | 46 | 23 |
| S- I+ | 10 | 32.8-38.5 | 35.8 | 0 | 0 |
| S+ I- | 10 | 39.6-51.0 | 46.6 | 50 | 39 |
| S- I- | 10 | 34.2-40.2 | 37.6 | 3 | 0 |
| S+ I+ | 20 | 34.4-42.0 | 38.8 | 20 | 0 |
| S- I+ | 20 | 29.0-34.3 | 32.3 | 0 | 0 |
| S+ I- | 20 | 34.5-42.3 | 38.3 | 7 | 0 |
| S- I- | 20 | 30.5-34.1 | 32.4 | 0 | 0 |
| Air | | 34.4-48.9 | 42.7 | 43 | 13 |

1. S+ = solarization; S- = No solarization; I+ = Irrigation; I- = No irrigation.

**Table 4. Effect of soil solarization (S) and irrigation (I) treatments on nitrate and ammonium nitrogen content in soil (mg $kg^{-1}$) of different depths of a Vertisol (BIL 2B and BIL 2C), ICRISAT Center, 1984/85.**

| | $NO_3$-N | | | | | | | | | $NH_4$-N | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0-15 cm | | | 15-30 cm | | | 30-45 cm | | | 0-15 cm | | | 15-30 cm | | | 30-45 cm | | |
| | I-[1] | I+ | Mean | I- | I+ | Mean | I- | I+ | Mean | I- | I+ | Mean | I- | I+ | Mean | I- | I+ | Mean |
| Pigeonpea experiment (BIL 2B) | | | | | | | | | | | | | | | | | | |
| S- | 5.0 | 5.6 | 5.3 | 5.0 | 4.2 | 4.6 | 4.5 | 4.5 | 4.5 | 3.8 | 4.6 | 4.2 | 5.0 | 3.6 | 4.3 | 6.1 | 4.9 | 5.5 |
| S+ | 10.8 | 16.2 | 13.5 | 6.0 | 10.4 | 8.2 | 4.3 | 5.7 | 5.0 | 4.1 | 4.3 | 4.2 | 5.3 | 3.8 | 4.6 | 6.1 | 4.9 | 5.5 |
| Mean | 7.9 | 10.9 | | 5.5 | 7.3 | | 4.9 | 5.1 | | 4.0 | 4.4 | | 5.2 | 3.7 | | 6.1 | 4.9 | |
| SE(1)[2] | | 1.54 | | | 1.15 | | | 0.79 | | | 0.46 | | | 0.51 | | | 0.74 | |
| SE(2) | | 1.68 | | | 1.22 | | | 0.87 | | | 0.68 | | | 0.45 | | | 0.38 | |
| SE(3) | | 2.27 | | | 1.68 | | | 1.18 | | | 0.82 | | | 0.69 | | | 0.84 | |
| SE(4) | | 2.37 | | | 1.72 | | | 1.23 | | | 0.95 | | | 0.64 | | | 0.54 | |
| Chickpea experiment (BIL 2C) | | | | | | | | | | | | | | | | | | |
| S- | 2.7 | 3.8 | 3.2 | 4.0 | 3.4 | 3.7 | 2.6 | 6.1 | 4.4 | 3.3 | 3.4 | 3.4 | 6.0 | 6.0 | 6.0 | 6.1 | 6.5 | 6.3 |
| S+ | 3.3 | 15.3 | 9.3 | 7.2 | 10.1 | 8.6 | 4.2 | 5.0 | 4.6 | 3.4 | 4.6 | 4.0 | 6.7 | 5.0 | 5.8 | 5.3 | 5.0 | 5.2 |
| Mean | 3.0 | 9.6 | | 5.6 | 6.8 | | 3.4 | 5.6 | | 3.4 | 4.0 | | 6.4 | 5.5 | | 5.7 | 5.8 | |
| SE(1) | | 1.02 | | | 0.96 | | | 0.97 | | | 0.47 | | | 0.73 | | | 0.80 | |
| SE(2) | | 1.06 | | | 0.76 | | | 0.64 | | | 0.54 | | | 0.39 | | | 0.38 | |
| SE(3) | | 1.47 | | | 1.22 | | | 1.16 | | | 0.72 | | | 0.83 | | | 0.88 | |
| SE(4) | | 1.50 | | | 1.07 | | | 0.90 | | | 0.76 | | | 0.56 | | | 0.54 | |

1. S- = No solarization; S+ = Solarization; I- = No irrigation; and I+ = Irrigation.
2. SE(1), SE(2), SE(3), and SE(4) are standard errors (±) for comparing irrigation effects, solarization effects, irrigation at same level of solarization, and solarization at same level of irrigation, respectively.

the soil was irrigated before solarization (Table 4); however, this effect extended only to a depth of 30 cm. Soil $NH_4$-N levels were not affected by solarization at any depth. Similar results were obtained during the 1986/87 season (results not presented).

## Weed growth

Solarization markedly decreased weed growth (Fig. 3). Most annual weed species were effectively suppressed by solarization; however, the perennials, such as *Cynodon dactylon*, *Cyperus rotundus*, and *Convolvulus arvensis*, gradually recovered. This was most noticeable in the chickpea experiment, which was left fallow after the completion of solarization treatments in June until the sowing in October-November.

Solarization for 2 successive years was most effective in suppressing weeds (Fig. 4). There was a residual effect of solarization in the previous year but solarization in the current year was more effective.

## Soil insects and other arthropods

Our attempts to monitor the effects of solarization on soil insects and other arthropods were unsuccessful due to inadequate natural populations in the experimental field.

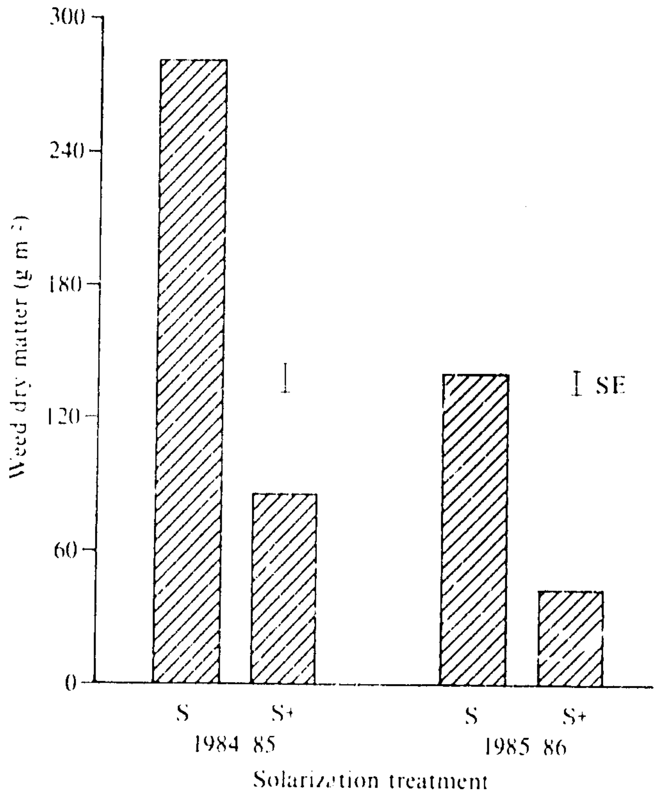


**Figure 3. Main effects of solarization on weed dry-matter production in the pigeonpea experiments conducted in 1984/85 and 1985/86 cropping seasons in field BIL 2B. S+ = solarized; S = nonsolarized.**

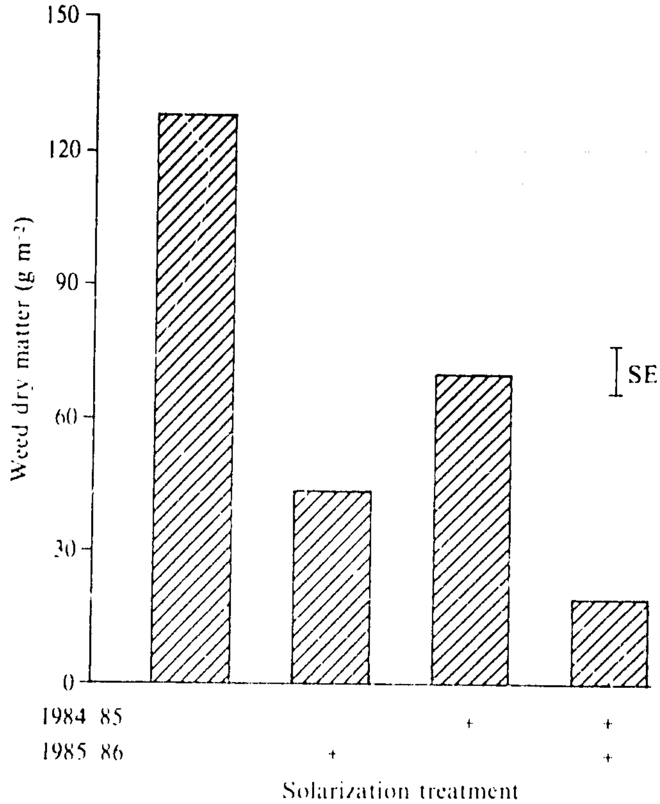


**Figure 4. Cumulative and residual effects of solarization on weed growth in the pigeonpea experiment conducted over 2 years in field BIL 2B. Weed masses are means of irrigated and nonirrigated treatments for the 1985/86 cropping season. Presence (+) or absence ( ) of solarization treatments is indicated.**

## Nematodes

The population of all parasitic nematodes of pigeonpea was markedly affected by solarization in the 1984/85 season (Fig.5a). Included in this population were *Heterodera cajani* cysts, eggs, and larvae; *Rotylenchulus reniformis*; *Helicotylenchus retusus*; and *Pratylenchus* spp. Solarization with irrigation was most effective in reducing populations of cysts, eggs, and larvae. The effect of solarization on total nematode population in the 1985/86 season was similar to that in the 1984/85 season, except that *H. cajani* cysts, eggs, and larvae in the cysts, were not affected. This was probably due to a shorter duration of solarization in this season. A residual effect of solarization was not apparent on the parasitic nematode population in the following year.

In the chickpea field, the effect of solarization on the total nematode population parasitic on chickpea, including *H. retusus*, *Pratylenchus* spp, *R. reniformis*, *Tylenchorhynchus* spp, and *Heterodera* spp larvae, was significant and drastic (Fig. 5b). The nematode population remained lower during the entire cropping season. A residual effect of solarization was also not apparent for chickpea plant parasitic nematodes.

## *Fusarium* population and wilt incidence

Just before solarization, both chickpea and pigeonpea wilt pathogen populations were more than 1000 propagules (g of soil)$^{-1}$. There was a large reduction in the population of both pathogens due to solarization in both dry and irrigated conditions immediately after the solarization period (Figs. 6-7). In the nonsolarized treatment, there was an increase in *Fusarium* propagules during this period. The *Fusarium* population remained at low levels in solarized plots throughout the growing season for both

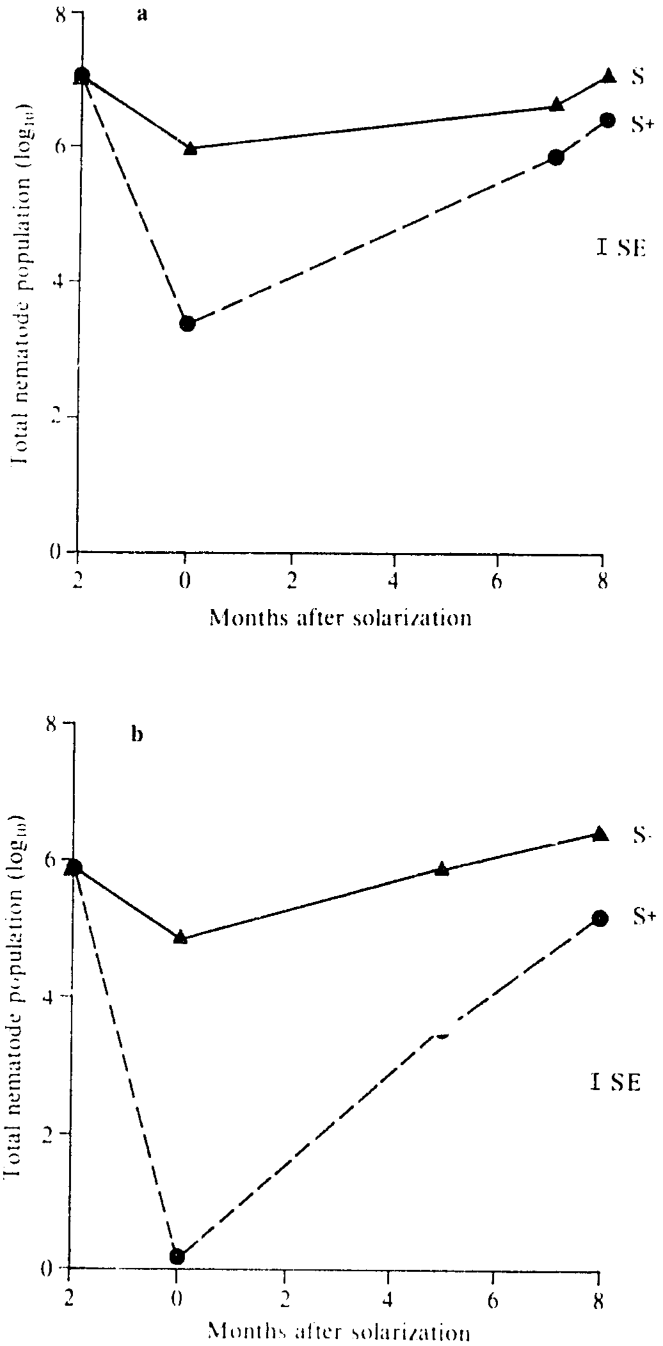


**Figure 5. Effect of solarization on the total plant parasitic nematode population (mean of irrigated and nonirrigated treatments) of (a) pigeonpea and (b) chickpea with time after solarization, fields BIL 2B and BIL 2C, 1984/85 cropping season. S + = solarized; S = nonsolarized.**

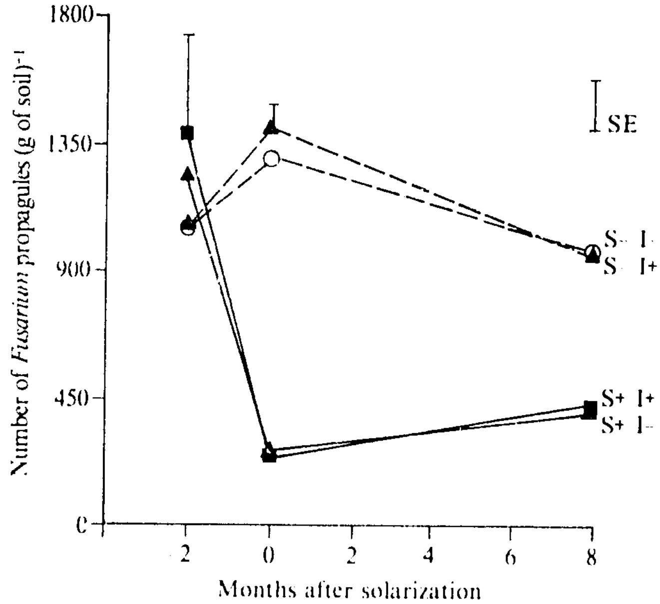


**Figure 6. Effect of solarization on numbers of *Fusarium* propagules in pigeonpea plots in field BIL 2B in the 1984/85 cropping season. Presence (+) or absence ( ) of solarization (S) or irrigation (I) treatments is indicated.**

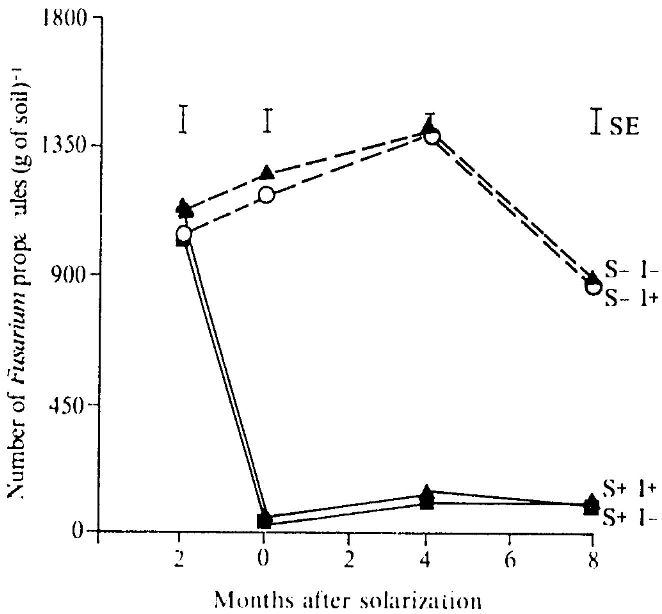


**Figure 7. Effect of solarization on numbers of *Fusarium* propagules in chickpea plots in field BIL 2C in the 1984/85 cropping season. Presence (+) or absence ( ) of solarization (S) or irrigation (I) treatments is indicated.**

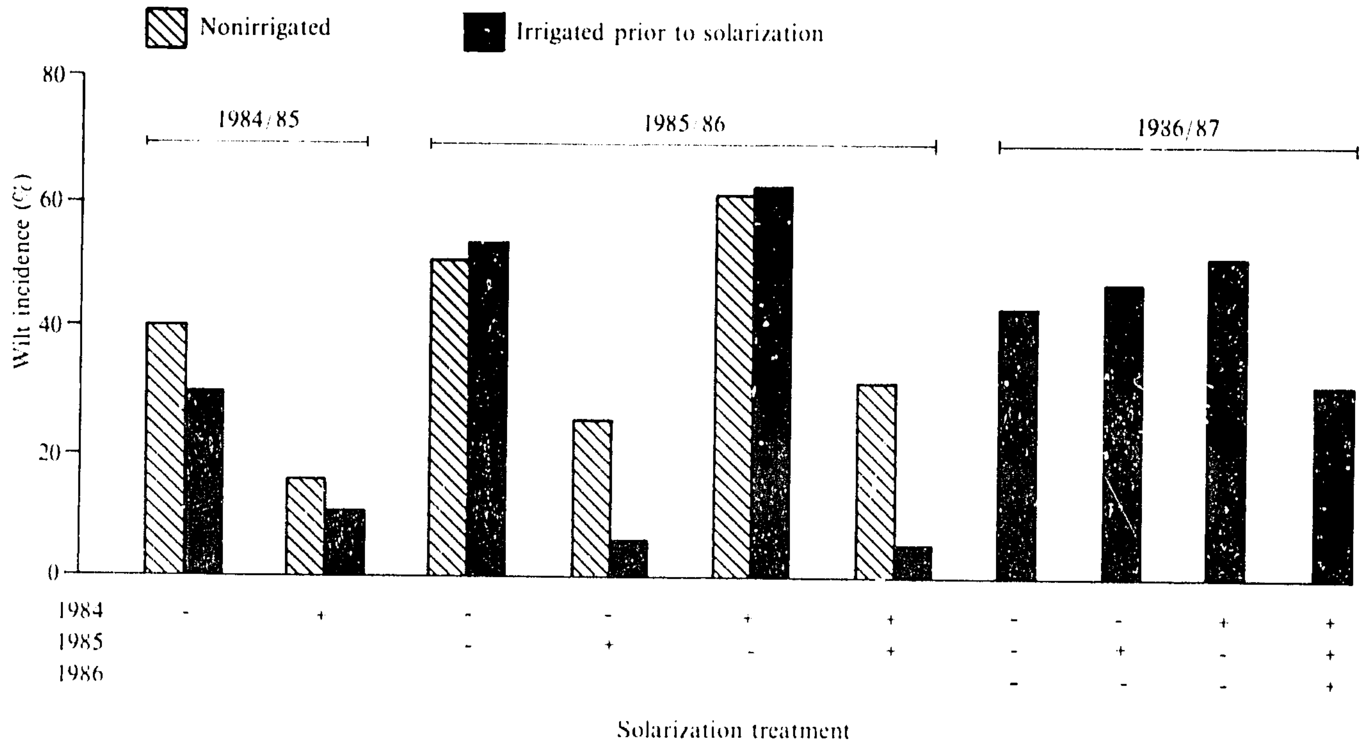


Figure 8. Effect of solarization on wilt incidence in wilt-susceptible pigeonpea genotype LRG 30 in a wilt-sick plot (BIL 2B) over three seasons. Presence (+) or absence ( ) of solarization treatments is indicated.

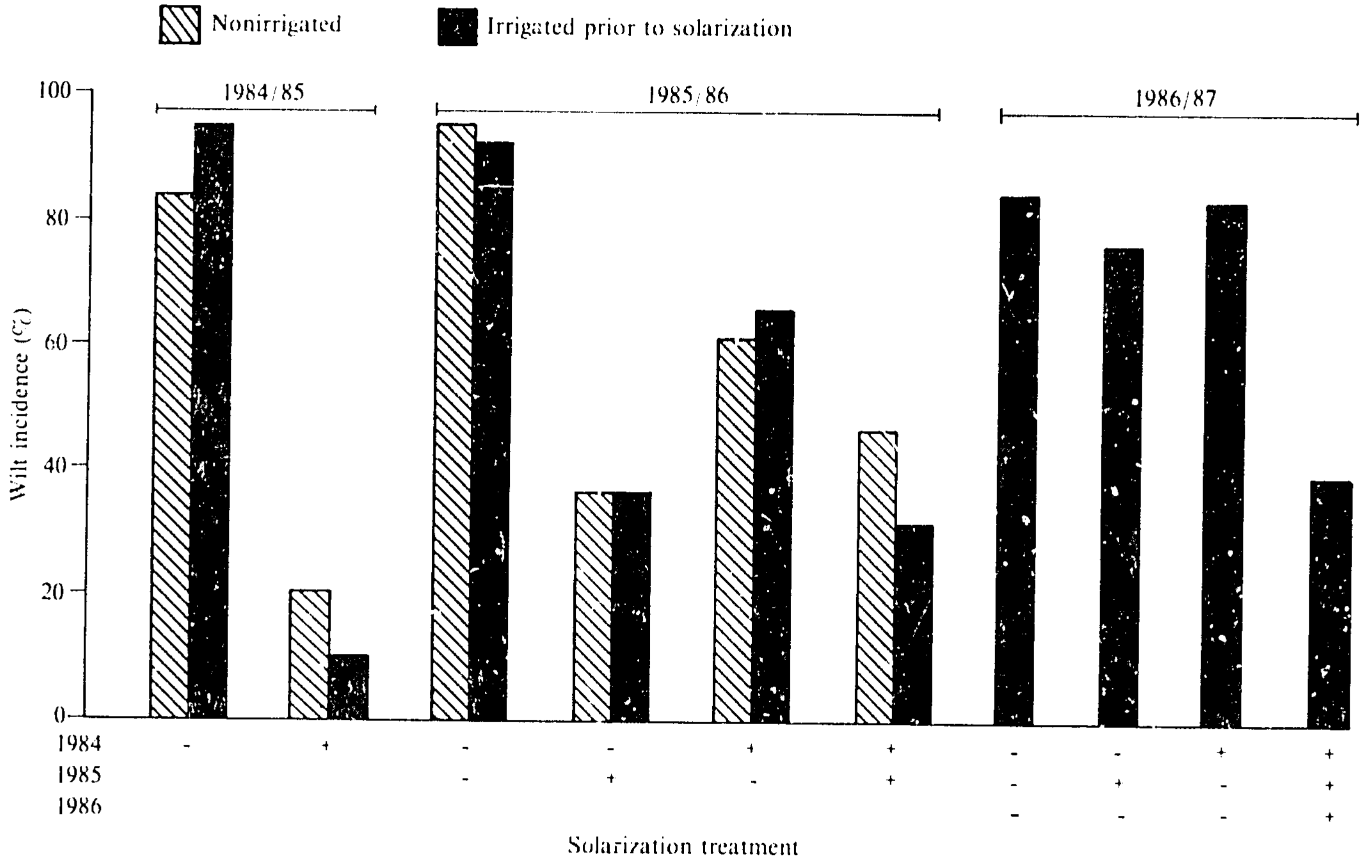


Figure 9. Effect of solarization on wilt incidence in wilt-susceptible chickpea genotype ICCV 1 in a wilt-sick plot (BIL 2C) over three seasons. Presence (+) or absence ( ) of solarization treatments is indicated.

crops. The beneficial effect of solarization in reducing the population of *Fusarium* was confirmed in both chickpea and pigeonpea experiments conducted in the 1985/86 season. The effect of solarization in 1984 on *Fusarium* propagule population extended into the second season.

Solarization reduced wilt incidence in pigeonpea under both irrigated and nonirrigated conditions (Fig. 8). The effect of solarization in 1984 was not apparent in the 1985/86 season (Fig. 8), even though the population of *Fusarium* propagules was lower than in the nonsolarized treatment.

Effects of solarization on wilt incidence in chickpea were dramatic (Fig. 9). Significant residual effects of solarization could be seen in the subsequent seasons, but the 1st year levels were not matched subsequently (Fig. 9).

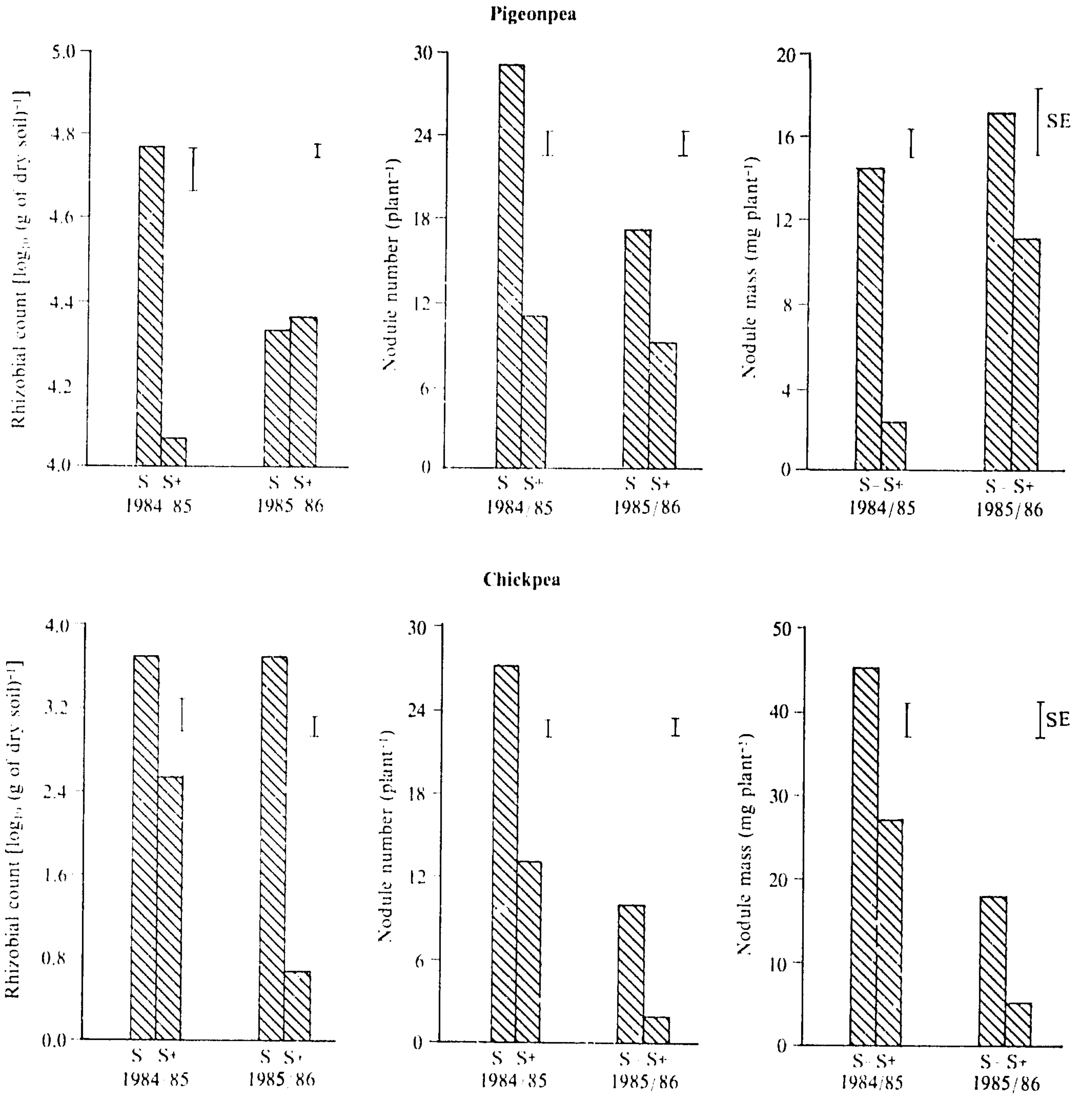


**Figure 10. Effect of presence (S+) and absence (S–) of solarization in irrigated treatments on soil populations of *Rhizobium* and nodule number and mass for pigeonpea in field BIL 2B and chickpea in field 3IL 2C over two seasons.**

## Rhizobial population and nodulation

Solarization did not significantly affect rhizobial population or nodulation of either crop in the nonirrigated treatments but it caused a significant reduction in these parameters in the irrigated treatments (Fig. 10). However, no effects were observed for pigeonpea in 1985 86, probably due to the reduced duration of solarization. Despite these reductions, shoot dry matter was not reduced in the solarized treatment at the time of nodulation sampling, perhaps due to the compensatory effect of solarization in enhancing nitrate concentrations in this treatment.

## Growth and yield of pigeonpea

Stimulatory effects of solarization on plant growth were obvious for both wilt-susceptible and wilt-resistant genotypes in all experiments (Figs. 11-13). Differences in plant height were apparent from early-growth stages (Fig. 14). Solarization reduced mean time to 50% flowering and to maturity. For example, in 1984 85 flowering period was reduced by 10 days for LRG 30 and by 12 days for ICP 8863 and time to maturity reduced by 60 days for LRG 30 and 19 days for ICP 8863. The corresponding values for the repeat experiment in 1985 86 were 10 days and 2 days for flowering and 8 days and 2 days for maturity.

Solarization markedly increased dry-matter production and seed yield of both genotypes in all 1st year experiments (Fig. 15). These increases were greater for LRG 30 than ICP 8863 and

Figure 12. Response of the wilt-susceptible pigeonpea genotype LRG 30 to solarization in BIL 2B in October 1985. The plot in the foreground was not solarized and most plants have died of wilt. The plot in the background was solarized.

Figure 11. General view of pigeonpea solarization experiment in field BIL 2B in December 1986. Plots with better growth received solarization treatment.

Figure 13. Response of the wilt-resistant pigeonpea genotype ICP 8863 to solarization in BIL 2B in October 1985. The nonsolarized plot is in the foreground and the solarized plot in the background.

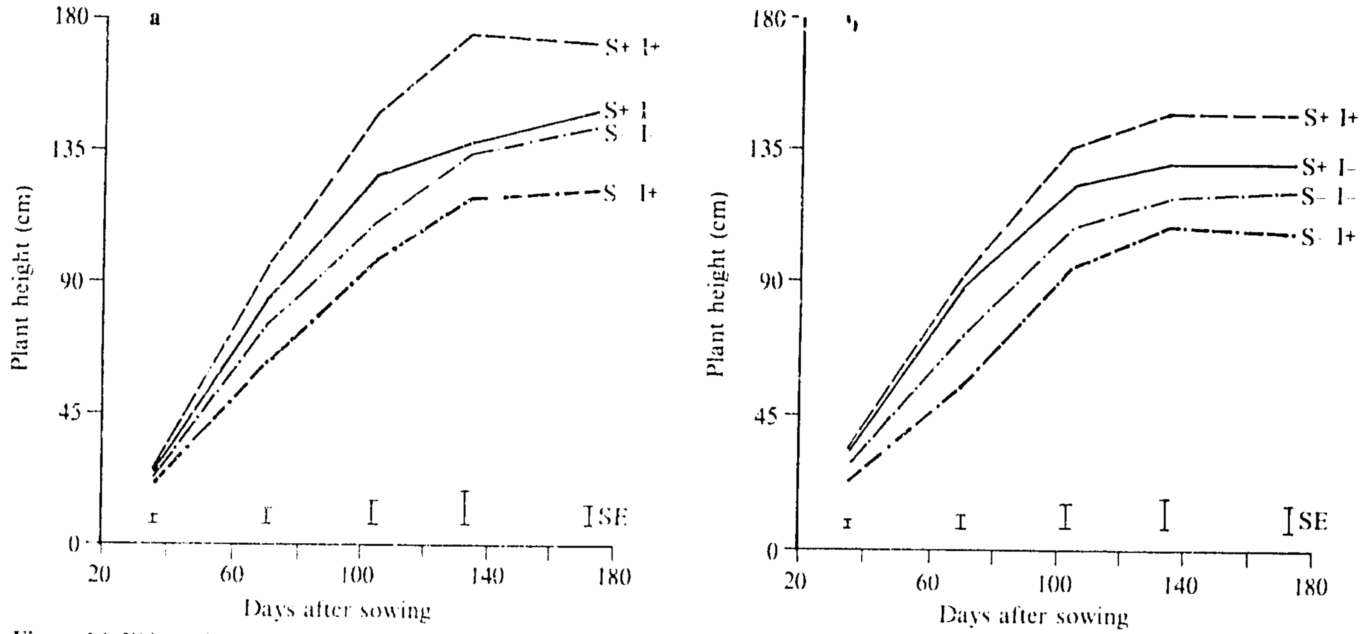


Figure 14. Effect of solarization and irrigation treatments on plant height (cm) at different growth stages of pigeonpea genotypes (a) LRG 30 and (b) ICP 8863 grown in the repeat experiment on field BIL 2B in the 1985/86 cropping season. Presence (+) or absence (-) of solarization (S) or irrigation (I) treatments is indicated.

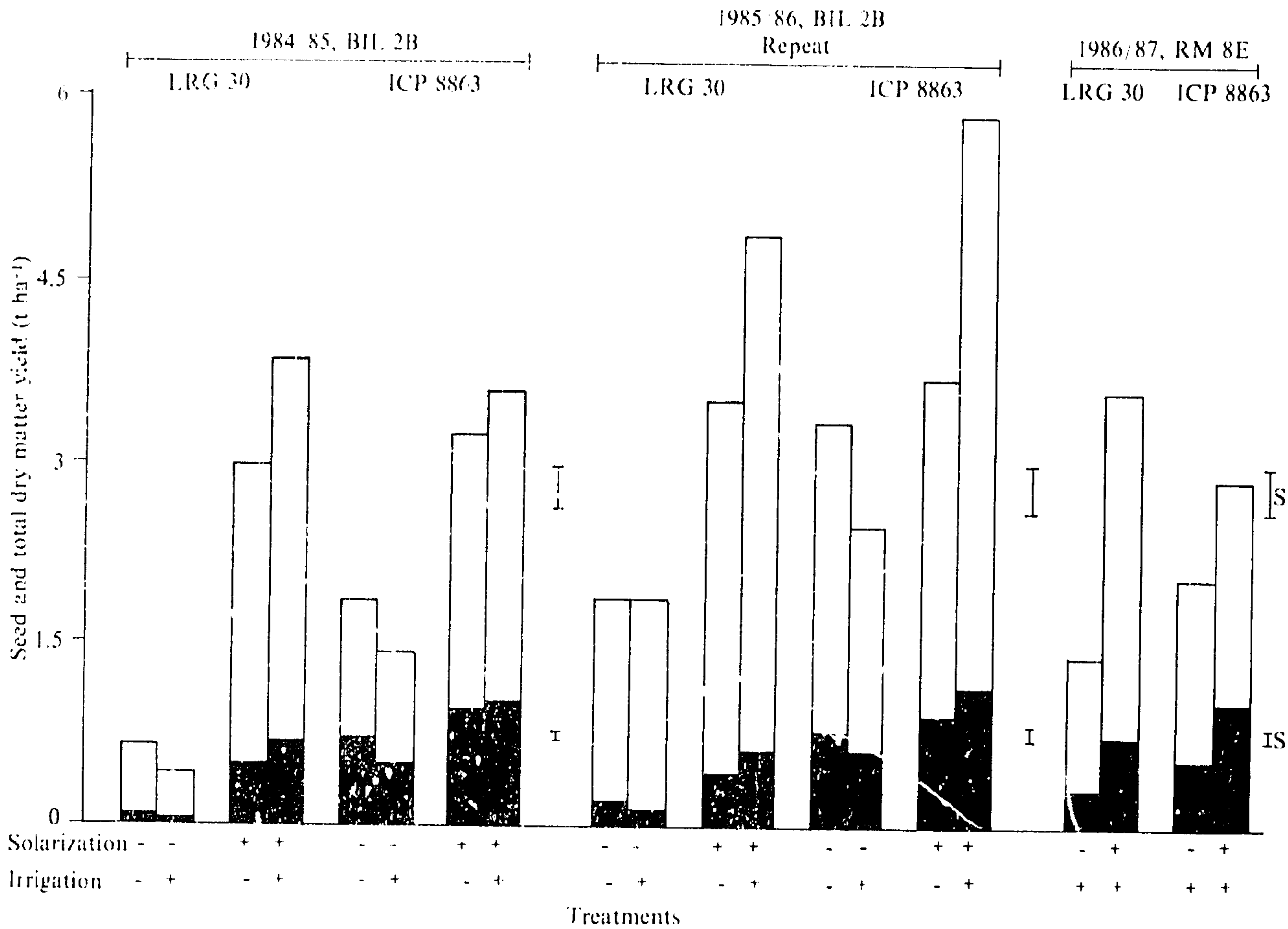


Figure 15. Effect of solarization and irrigation treatments on seed (*shaded*) and total dry matter (*entire bar*) yields of wilt-susceptible (LRG 30) and wilt-resistant (ICP 8863) pigeonpea genotypes. Presence (+) or absence (-) of solarization or irrigation treatments is indicated.

in the presence of irrigation. Improved seed yields resulted from increased pods and seeds plant⁻¹; there were no significant treatment effects on seed size.

There were no significant residual effects of solarization in the previous season on total dry-matter or seed yield for either genotype (Fig. 16). Further, there were no differences between solarization for 2 successive years and solarization in the current year only (1985/86 data of Fig. 16). Only solarization in the current season caused significant differences, confirming results of the 1st year (Fig. 15). However, in 1986/87, ICP 8863 did not respond to solarization.

## Growth and yield of chickpea

Growth and yield of chickpea were relatively poor in all experiments. This was primarily due to drought stress, as crop growth had to rely on residual soil moisture because of limited access to irrigation in these fields. Further, in the first two seasons, land was not cultivated prior to chickpea sowing for fear of cross-contamination between plots. Nevertheless, large effects of solarization were apparent (Fig. 17).

In the 1st year of the experiment in BIL 2C (1984/85), virtually all plants of the wilt-susceptible genotype ICCV 1 were

**Figure 17. General view of chickpea solarization experiment in field BIL 2C in December 1986. Plots with poor stands have chickpea genotype ICCV 1, without solarization. The four rows with reasonable plant stand in the two upper right plots with poor stand had been treated with *Fusarium* antagonists.**

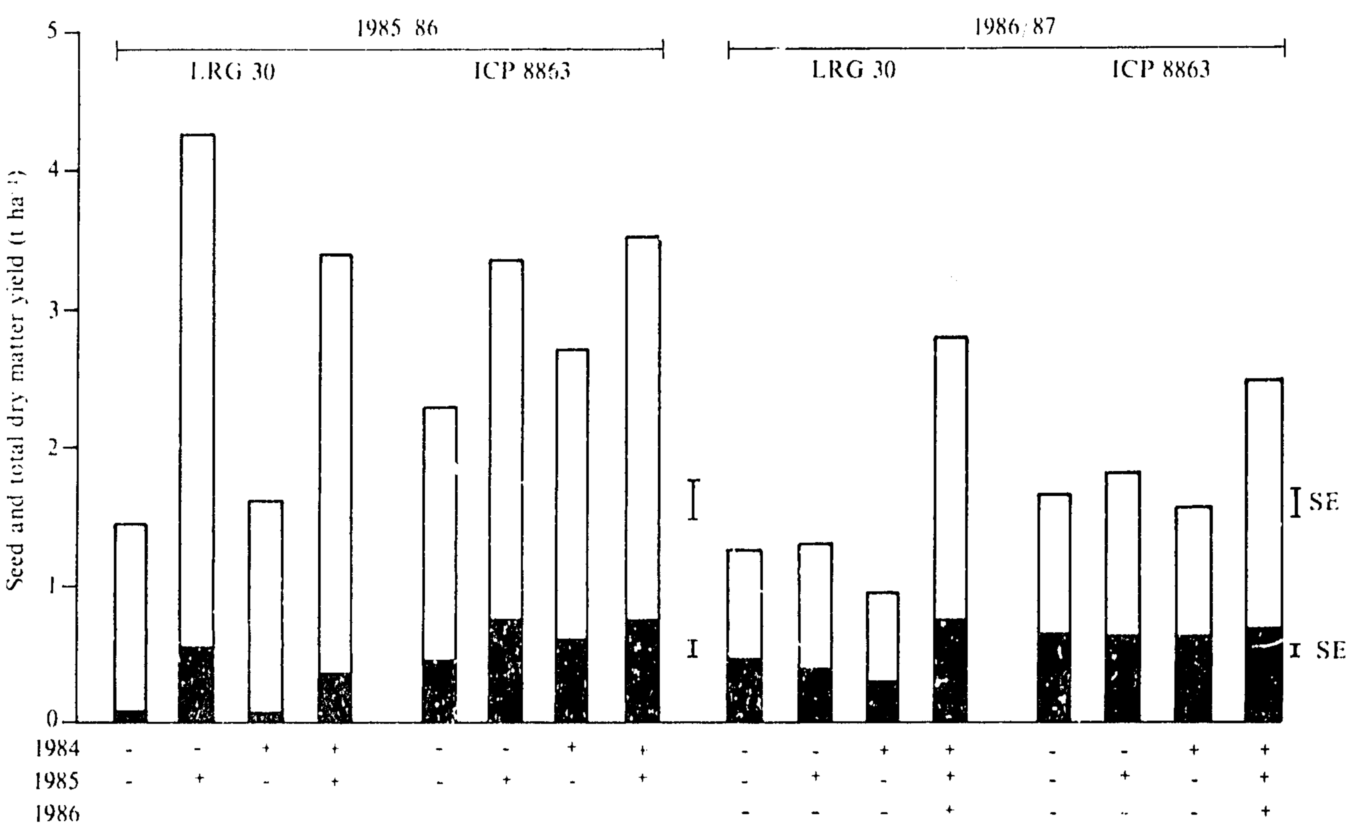


**Figure 16. Residual effects of solarization on seed (*shaded*) and total dry matter (*entire bar*) yields of pigeonpea grown in field BIL 2B in 1985/86 and 1986/87 seasons. Data are pooled for irrigation treatment in 1985/86 as this treatment did not significantly affect yields. Presence (+) or absence (-) of solarization treatments is indicated.**

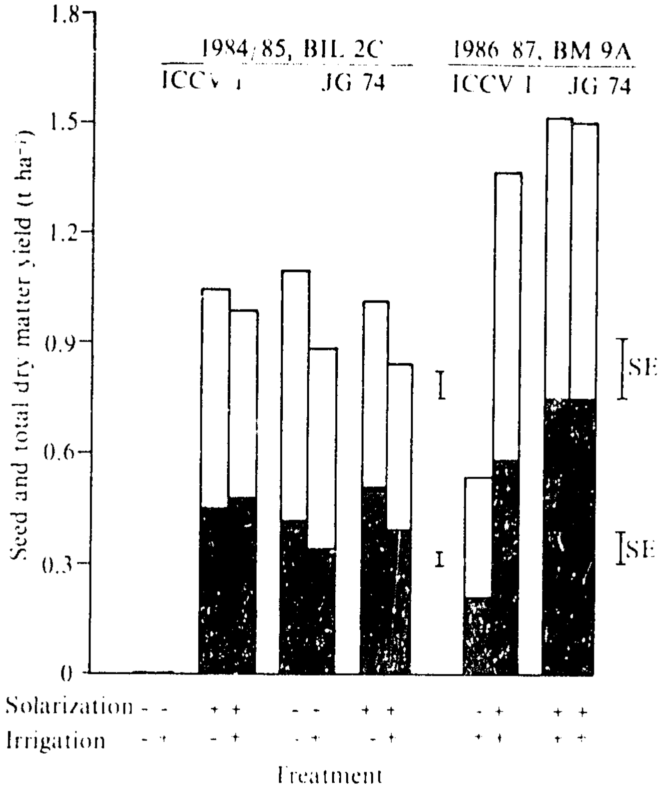


**Figure 18. Effect of solarization and irrigation treatments on seed (*shaded*) and total dry matter (*entire bar*) yields of wilt susceptible (ICCV 1) and resistant (JG 74) chickpea genotypes. Yield and dry matter are not shown for ICCV 1 for nonsolarization treatment as it died completely even before reaching 50% flowering. Presence (+) or absence ( ) of solarization or irrigation treatments is indicated.**

killed before maturity in nonsolarized plots and no yield was obtained (Fig. 18). In the wilt-resistant genotype JG 74, there was a 23% increase in seed yield due to solarization in the irrigated treatment and 17% in the nonirrigated treatment, mainly due to an increase in the 100-seed mass. The positive response of ICCV 1 to solarization was confirmed in field BM 9A in 1986/87 (Fig. 18).

In contrast to pigeonpea, there were clear residual effects of solarization on ICCV 1 in subsequent seasons in BIL 2C (Fig. 19). In 1985/86, two successive solarizations had the same effect as a single solarization in the current year. In 1986/87, growth and yield decreased with time from the previous solarization. There were no significant responses of JG 74 to solarization in the second and third seasons in BIL 2C (Fig. 19).

## Discussion

The increases in soil temperature achieved by soil solarization in this study compare favorably with those reported in temperate climates; i.e., about 10°C in the surface soil 5-cm deep (Katan 1981; Horiuchi 1984). In the present study, temperatures under polythene sheeting exceeded 60°C at 5 cm and reached 42°C at 20 cm soil depth, which are in the lethal range for many microorganisms (Pullman et al. 1981). This increase in soil temperature with solarization has been considered as the major driving force for the various biological and physicochemical changes in the soil that affect plant growth (Katan 1981).

The effects of solarization in increasing growth and yields of the wilt-susceptible genotypes can primarily be attributed to harmful effects on the wilt pathogen. The reduction in wilt incidence with solarization was accompanied by large reductions in the numbers of *Fusarium* propagules specific to either pigeonpea or chickpea. Thermal inactivation of fungal propagules could be the reason for such reductions (Katan 1981; Pullman et al. 1981). Solarization was more effective in reducing the *Fusarium* propagules of chickpea than of pigeonpea, with consequent greater effects on growth and yield of wilt-susceptible chickpea; this may be due to differential thermosensitivity of the pathogens or their differential distribution in the soil profile. Although it has been reported that moisture is a crucial factor determining the effectiveness of soil solarization (Katan et al. 1976), irrigation prior to solarization did not significantly enhance reduction of *Fusarium* propagules. Apparently whatever little soil moisture was present in the nonirrigated solarized treatment was sufficient to thermally inactivate the *Fusarium* propagules.

Biological control of soil pathogens by means other than thermal inactivation is also encouraged by solarization (Katan 1981). *Fusarium* propagules were not completely destroyed by solarization and yet control of wilt disease was very effective, particularly in chickpea. This indicates involvement of other factors. It is possible that *Fusarium* propagules were weakened by heat to the extent that they become poor competitors with other soil microorganisms. Indications have been obtained recently that fungal antagonists, encouraged by solarization, can reduce wilt incidence in both crops (M.P. Haware, ICRISAT, personal communication 1986; see Fig. 17).

That additional factors to the effects of solarization on fusarium wilt are involved is evidenced by the stimulatory effects of solarization on early-growth rates in the wilt-susceptible pigeonpea genotype and on growth and yield of the wilt-resistant pigeonpea genotype. This "increased growth response" (IGR), additional to the effect of controlling the target pathogen, has been previously documented and discussed (Katan 1981). However, IGR effects were not so apparent in chickpea and effects of solarization on growth and yield in that crop can almost entirely be attributed to reaction to fusarium wilt. Factors likely to be of importance for IGR in this study include control of plant-parasitic nematodes and increased mineralization of soil nitrogen. Stapleton et al. (1985) reported that solarization increased production of both $NH_4$-N and $NO_3$-N. $NH_4$-N levels were not affected in the present study, presumably because of rapid conversion of $NH_4$ to $NO_3$. The enhanced availability of nitrate with solarization appeared to compensate for the reduction in rhizobial numbers and symbiotic activity in this treatment.

Reduction of weed infestation is another beneficial side effect of solarization. This could have been caused by direct thermal killing of weed seeds either before germination or soon after it had been induced by moisture in the solarized plots. However,

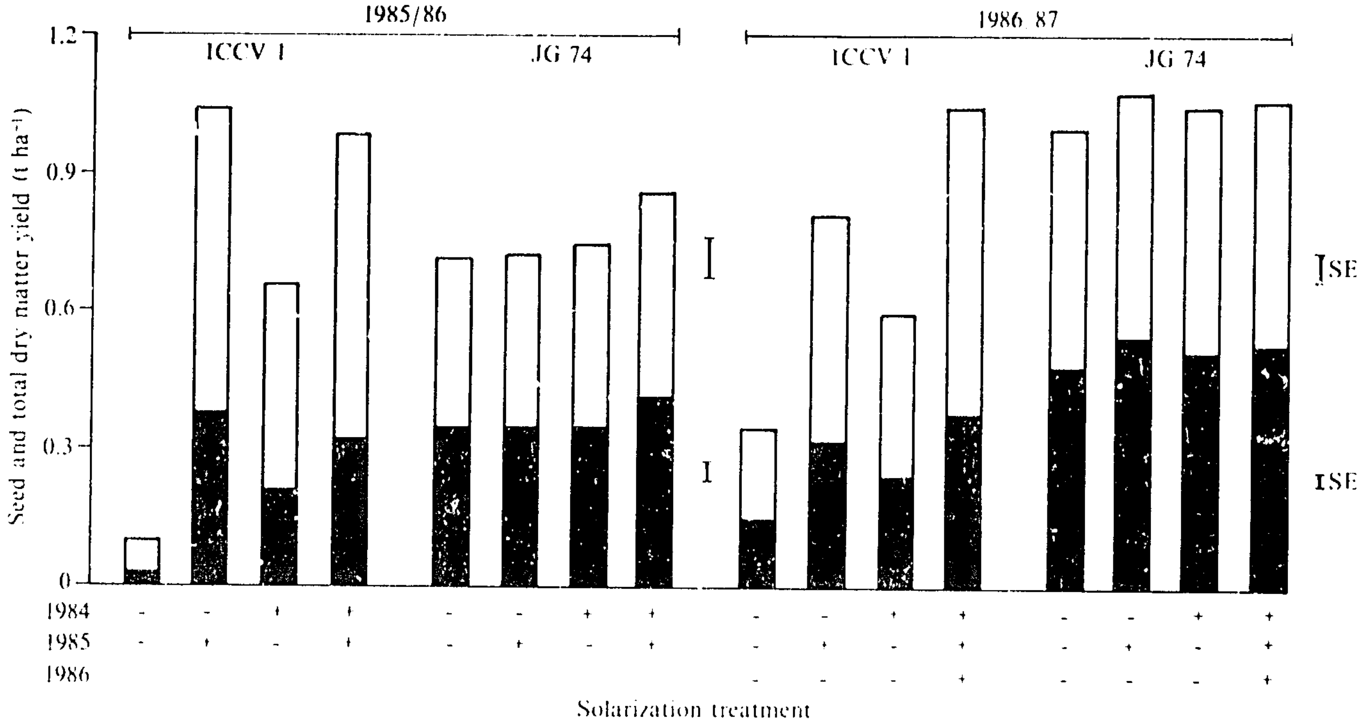


**Figure 19. Residual effects of solarization on seed (*shaded*) and total dry matter (*entire bar*) yields of chickpea grown in field BIL 2C in 1985/86 and 1986/87 seasons. Data are pooled for irrigation treatment in 1985/86 as this treatment did not significantly affect yields. Presence (+) or absence ( ) of solarization treatments is indicated.**

solarization was less effective in controlling perennial weeds, probably due to the deeper distribution of their propagating tissues in the soil, where temperature increases were less.

Stimulatory effects of solarization were encouragingly consistent across locations and time. Residual effects of solarization were substantial and consistent for chickpea but not apparent for pigeonpea. Further, in pigeonpea there were indications of greater wilt incidence in plots solarized in previous years but not receiving solarization in the current season. This may indicate an enhanced capacity for reinvasion of the pigeonpea wilt pathogen.

Irrigation before solarization is generally recommended to obtain effective disease control (Katan 1981). In the present study, solarization was effective without irrigation, although at least for pigeonpea, effectiveness did improve with irrigation. Thus, irrigation capability is not a prerequisite to effective solarization.

## Implications

Although beneficial effects of solarization have been clearly demonstrated for chickpea and pigeonpea in peninsular India, economic considerations would limit use of this technique for these crops in commercial agriculture. Both of these crops are normally grown extensively, under rainfed conditions, with little input and little return. Development and use of disease resistant or tolerant genotypes would be more practical for disease-infested land in these circumstances. Nevertheless, there are situations where solarization is feasible for these particular crops. One is on research stations where it is necessary to repeatedly grow genotypes affected by wilt or other diseases, including nematode-caused diseases, on the same area of land. Examples would include crossing blocks and germplasm-assessment studies. Solarization has already been adopted as a practice for these circumstances at ICRISAT Center; it is safer, more economic, and possibly as effective as soil fumigation with chemicals. Another possibility of using solarization for these crops is in production of disease-free seed, either on research stations or on a commercial scale. It has been found that fusarium wilt can be seed-transmitted and thus use of disease-free land is necessary for seed-production plots.

For crops of high value per unit area, such as vegetables, use of solarization becomes more economically feasible for control of soilborne diseases. The economics would improve with the advent of cheaper, thinner, ultra-violet-light resistant polythene sheeting (Katan 1984). We would recommend that the technique be evaluated for high-value crops prone to soilborne diseases in the environment of peninsular India. We have summarized our recommendations for applying solarization treatments, for any crop, in the Appendix.

Solarization may also be used as an experimental tool to modify populations of soil microorganisms. At ICRISAT Center, we are using the technique in studies of *Rhizobium* ecology, particularly to understand soil colonization by inoculated strains of chickpea rhizobia.

Katan (1984) has summarized our present knowledge of solarization and suggested future research directions to develop the technique further. He pointed out that solarization should not be regarded as a universal method, but rather as an additional option for pest and disease control, for use in conjunction with other methods.

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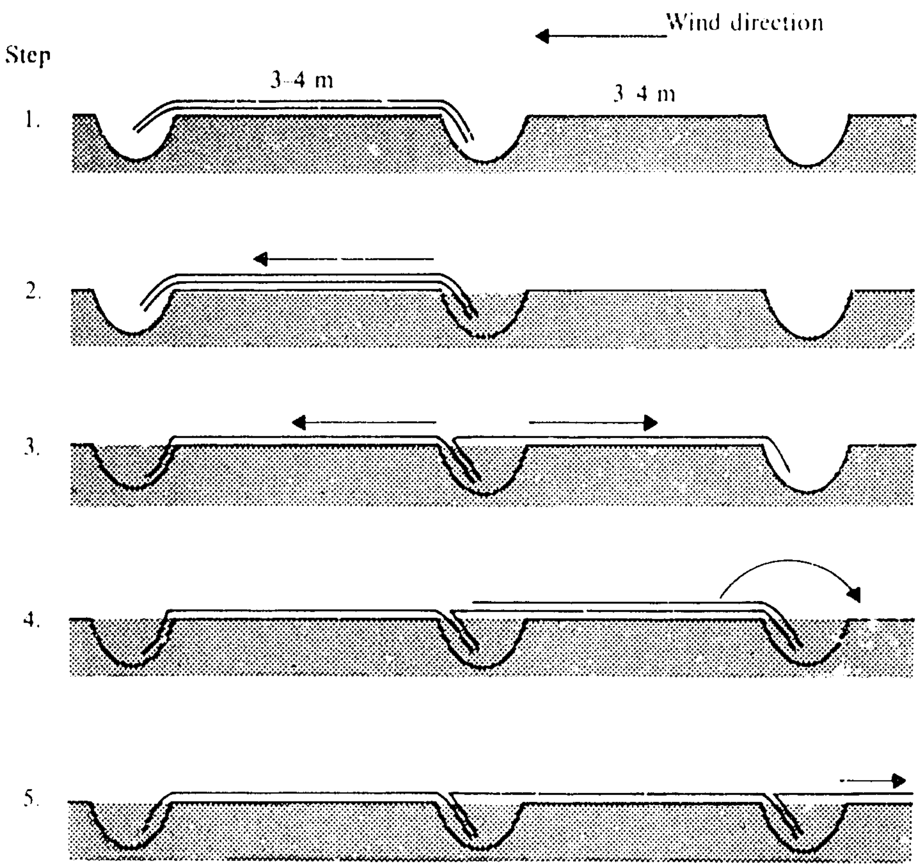
## Appendix: Hints on Application of Solarization

On the basis of our experience with solarization over 3 years, we consider it worthwhile to suggest some details of technique that should ensure more effective solarization:

1. Solarization should be conducted for at least 6 weeks during the hottest part of the year.
2. The land to be solarized should be thoroughly cultivated and then leveled so as to minimize such protrusions as clods, stubble, and stones in the area to be solarized, to prevent the tearing of polythene sheeting. We have normally used land prepared into 1.5-m wide broad beds and furrows.
3. If possible, a 50-mm irrigation should be given prior to laying of the polythene sheeting.
4. Clear, transparent (not black or colored) polythene sheeting of 25–100 $\mu$m thickness should be used. Thinner sheeting is more effective in trapping heat but thickness should be balanced against durability. The width of the sheeting should be about 3 m, preferably without any joint.
5. The polythene sheeting should be applied immediately after irrigation. It is best to apply the sheeting at dawn, when it is least windy.
6. Two edges of polythene sheets should be inserted in the furrows as shown in Figure 20. The edges should be buried and the top sheet opened out, as pages of a book. The process may be repeated, by aligning another sheet with a free edge, burying the edges and opening the sheets, until the required area is covered with sheeting. All free edges should be buried and the soil around them compacted so as to prevent escape of heated air or soil moisture.
7. It is necessary to allow for a buffer zone of at least 0.5 m, but preferably >1 m, around the edges of solarized area due to dilution of heat near the edges. Further, sufficient space should be allowed between solarized areas for various operations and drainage channels.
8. Any holes appearing in the polythene sheeting should be sealed at the earliest opportunity. We have found silicone rubber sealant (Dow Corning Product No. 790, USA) to be effective. Holes can be easily recognized by absence of condensed moisture on the inner surface of the polythene sheeting.
9. Entry into plots covered with polythene sheeting should be avoided to the extent possible. If entry is necessary, such as for sealing leaks, bare feet or smooth-soled shoes are preferable.
10. To prevent flapping and tearing of polythene sheeting in the wind after some moisture has been lost from under the sheeting, it is recommended that weights be placed on the sheeting. The weights should not have sharp edges; we have successfully used plastic bags filled with soil.




1. Place ends of two sheets in furrow.
2. Bury with soil and compact soil.
3. Move top sheet away from bottom one. Bury edges of bottom sheet and compact soil.
4. If necessary, repeat the process by placing another sheet on the top, burying the two edges as in Step 2 and opening the top sheet.
5. Ensure all edges are thoroughly sealed with compacted soil.

**Figure 20. Recommended method of placing polythene sheeting for solarizing soil.**

11. It has been suggested (J. Katan, Faculty of Agriculture, the Hebrew University of Jerusalem, Israel, personal communication, 1985) that addition of fresh organic matter to solarized plots can enhance solarization effects, through production of volatile organic compounds that are toxic to pathogens. However, such compounds could also be phytotoxic and it is recommended that the effect of solarization with organic matter incorporation be experimentally tested for each particular crop site combination.
12. After solarization and prior to or during crop growth, irrigation water should not be allowed to flow from areas possibly contaminated with pathogens onto solarized plots. Use of sprinkler or irrigation through perforated pipes is thus recommended in this case.