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RESEARCH ARTICLE

Assessing designer seed and pink pigmented facultative microbes mitigating drought on cotton yield under rainfed condition

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Abstract

Fifty-one percentage of India's net sown area comes under rainfed agriculture which contributes to nearly 40% of total food production. But constant fluctuations in total rainfall and its distribution severely affect the yield of rainfed crops. Such uncertainty in crop production necessitates the need to enhance the productivity from rainfed areas to meet the growing population demand by adapting suitable technologies. Considering these constraints, a field trial was carried out during 2022-23 at Agricultural Research Station (ARS), TNAU, Kovilpatti, India to evaluate the impact of drought mitigation technology on sustainable yield and economics of cotton grown in dryland situations. The trial conducted in Factorial Randomized Block Design (FRBD), treatment comprised of sowing of hardened seed (1% KCl) and designer seed in factor A and 6 different drought mitigation technologies *viz*., Pusa hydrogel at 2.5 kg ha^{-1} as basal, Mepiquat chloride spray at 250 ppm at 45 and 60 DAS, Cycocel at 250 ppm as foliar spray at 45 and 60 DAS, Cotton plus at 6.25 kg/ha as foliar spray at flowering and boll development stage, Pink Pigmented Facultative Methylotraphs (PPFM) spray at 500 mL/ha at square formation, flowering and boll enlargement stage along with control (no soil/foliar application) in Factor B and simulated thrice. Sowing designer cotton seed along with spraying PPFM at 500 mL ha^{-1} at square growth, flowering and boll enlargement stages recorded higher growth attributes, yield attributes and yield of cotton under rainfed conditions. Hence, farmers can get a higher percentage of the total (gross) income (13.5 and 31), net income (return) (28 and 62) and B:C value (12 and 23) when adopting sowing of designer cotton seed with spraying PPFM at 500 mL/ha respectively.

Keywords: cotton; drought mitigation; economics; physiology; seed hardening; yield

Introduction

Cotton is globally an important fibre crop, also referred to as "White gold". India is the second biggest cotton user and exporter. According to the Ministry of Textiles, Government of India, India occupies the premier position globally in terms of cotton acreage, with an area of 130.6 lakh ha during the fiscal year 2022–23, constituting approximately 40% of the worldwide total area of 324.2 lakh ha. An estimated 67% of cotton produced in India is cultivated in rain-fed regions (1). The requirement for cotton bales goes on an increasing trend, while the production status is on a decreasing trend. Two vital weather factors *viz*., temperature and rainfall greatly influence the crop from germination to final productivity under rainfed conditions (2-4). With respect to productivity metrics, India is ranked 39th globally, achieving a yield of 447 kg per ha (1). The present productivity of rainfed areas (447 kg per ha) needs to be raised to meet the increasing population demand. The common feature of the rainfed ecosystem is characterized by complex deficiency, especially erratic and uncertain rainfall. This deficiency of rainfall may lead to dry spells and moisture deficit which affect plant growth and yield. Due to climate change the effect of water shortage in agriculture production has become more frequent (5). Any effort to mitigate the ill effects of moisture stress will definitely sustain the yield of rainfed cotton.

Cotton being a seed-sown crop, the process of seed hardening is an excellent method of inducing drought resistance as it modifies the biochemical and physiological nature. The seed hardening technique helps to lighten the negative impact of moisture deficiency during the later stage of crop production. Under drought conditions, seed hardening with CCC at 500 ppm or 2% KCl recorded higher proline accumulation, Chlorophyll Stability Index (CSI), Relative Water Content (RWC), Dry Matter Production (DMP) and leaf area at various phenological stages and yield of cotton (6). Designer seed is produced by treating the seeds with the addition of nutrients which includes KCl, bio inoculants and plant protectants for improved emergence and establishment. It has increased germination percentage, plant population at the harvest stage, bolls quantity, early flowering and kapas yield plot^{-1} (7). The shoot and root formation of *V. unguiculata* was improved by the application of silica nanoparticles (8).

Apart from seed treatment for drought tolerance, soil application of hydrogel contributes significant importance in rainfed agriculture. Hydrogel is an insoluble, synthetic polymer, with the capacity to suck up a huge volume of water (9) to the tune of 80 - 180 times its real volume (10). In areas of insufficient irrigation facilities, the hydrogel has huge potential as it increases water accessibility during the crop-growing period. Wheat's improved performance due to hydrogel application was evident in the field (5) when hydrogel was applied in alluvial sandy loam soil at 5 kg/ha along with FYM which drastically increased the soil physical properties like available soil moisture, hydraulic conductivity and field capacity (5).

Excessive vegetative growth under favourable growing conditions leads to yield losses in cotton, due to increased transpiration rate causing loss of stored water under rainfed conditions. In order to get a higher yield in cotton, restricted vegetative growth is necessary. Spraying of Mepiquat chloride inhibits gibberellin (GA) biosynthesis thereby hindering stem elongation (11, 12), which results in shorter shoot length (13) and shorter plant (14). In addition, shorter shoot lengths with more leaf chlorophyll content facilitate increased light interception, photosynthetic rate and light use efficiency (15). It also enhances cotton seed's oil and protein content and seed yield (16). Chlormequat spray regularly prevents shoot growth which increases the number of flower buds plant^{-1}. The number of sympodial branches, squares, bolls and kapas yield was significantly superior under Chlormequat chloride spray (17).

Minor and macro inorganic nutrients in sufficient quantities are necessary for better crop growth (18). If soil is deficient for any single nutrient it will affect the growth of plants, even though all others available are in excess quantity (19). Combined use of PPFM, mulching and hydrogel increased RLWC, CSI, yield attributes and yield of black gram under rainfed conditions by reducing evapotranspiration and increasing stored soil moisture (20). Above plant nutrients, growth regulators and hormones considerably increased plant growth, yield attributes and finally yield of cotton. Nutrients are extremely vital composites that are necessary for cotton growth and increased yield by improving the physiological efficiency of plants (21). TNAU Cotton Plus (contains all essential nutrients as well as plant growth regulators at a definite proportion) is a foliar formulation consortium that increases plant height, sympodial branches, chlorophyll content, total dry weight of the plant, RWC and ultimately the seed cotton yield by 10.2% than control when applied at 1.25% at flowering and boll formation stages (22).

Farmers practised low-input subsistence agriculture under rainfed conditions. South India receives 48% of total annual rainfall during the northeast monsoon season and it is characterized by highly erratic in terms of temporal and spatial distribution which leads to continuous crop failure (23). The main objective of the farmers is to get economic benefit from the amount invested by them. Such inconsistent weather situation necessitates an evaluation of various drought mitigation technologies for sustaining cotton production under rainfed conditions, increasing the yield and net income of rainfed farmers.

Material and Methods

Experimental site

Present field research was conducted at Agricultural Research Station, Kovilpatti, TNAU, India to evaluate various drought mitigation technologies on the performance of rainfed cotton. The study area is characterized as a semi-arid region having an average annual rainfall of 737 mm in which northeast monsoon rainfall is 340 mm. The average annual maximum and minimum temperatures were 35 °C and 22 °C, respectively. The experimental site has very deep vertisols with subangular blocky in structure and is taxonomically classified as *Typic Haplusterts*. Field capacity, permanent wilting point and bulk density were 35%, 14% and 1.29 mg g^{-1}, respectively. Electrical Conductivity is 0.32 dSm^{-1}, pH is 8.47 and available nitrogen, phosphorus and potassium were 160, 14.3 and 380 kg ha^{-1}, respectively.

Methodology

Genetically pure cotton variety, KC 3 were delinted and hardened by soaking in KCl (1%) solution for 6 h, then shade dried to get the original weight. Designer seeds were obtained by coating the hardened seeds with polymer at 3 mL kg^{-1} followed by Imidacloprid at 2 mL kg^{-1} and *Pseudomonas fluorescens* at 10 g kg^{1} and finally with *Azophos* at 120 g kg^{-1}. Pusa hydrogel is a polymer made up of polyacrylate super absorbent, which absorbs pure water to the tune of 350 times its original dry weight, then steadily releases it at the temperature of 40-50 °C (24). Depending on the soil texture, the Pusa hydrogel dosage was fluctuating from 2.5 to 5 kg ha^{-1}. Soils with high water holding ability (clayey) require less quantity of Pusa hydrogel i.e., 2.5 kg/ha while sandy soils having lower water holding ability require more quantity. The experimental site was a heavy clay texture and hence a lower dosage was used. Hydrogel was mixed with soil and placed 5 cm deep near dibbled cotton seeds.

TNAU Cotton Plus, a foliar formulation consortium which contains all essential nutrients along with plant growth regulators at a definite proportion was used for the present study. Pink-Pigmented Facultative Methylotrophs (PPFM) formulated by TNAU have the ability to produce ethylene, cytokinins, auxins and also GA which can enhance the growth of cotton was used for the experiments.

The treatment comprised of sowing of hardened seed (1% KCl) and designer seed in factor A and 6 different drought mitigation technologies *viz.*, Pusa hydrogel at 2.5 kg ha^{-1} at basal, Mepiquat chloride at 250 ppm spray at 45 and 60 DAS and Cycocel at 250 ppm spray at 45 and 60 DAS, Cotton Plus at 6.25 kg/ha as foliar spray at flowering and boll development stage, PPFM spray at 500 mL/ha at square formation, flowering and boll enlargement stage along with control (no soil/foliar application) in Factor B was attempted. The design of the experiment was FRBD and duplicated 3 times. Spacing adapted under rainfed conditions was 45 × 15 cm. Recommended fertilizer and plant safety actions were carried out during the entire cropping period.

Relative leaf water content (RLWC)

In each plot, fully opened 6 flag leaves from randomly chosen plants were selected then top and bottom and any dead or dying tissues were cut off from all the leaves together, with the remaining 5 cm mid-section. The samples were immediately placed into the pre-weighed tubes, sealed with a lid and placed into a cooled insulated container (at around 10 °C - 15 °C; but not frozen). After taking the weight of all samples (tube W + FW) in each tube, 1 mL of distilled water was added, placed the sample tubes in a refrigerator (at 4 °C in darkness) for 24 h (for leaves to reach full turgor). Leaf samples were taken out of the tube quickly and carefully blot-dried with a paper towel and weighed the sample (TW: turgid weight). Finally, leaf samples were placed in a labelled envelope and dried at 70 °C for 24 h, or until attaining constant mass then reweighed the leaf samples (DW: dry weight) (25). RLWC was calculated by using the formula below:

$$\text{RLWC (\%)} = \frac{(\text{FW-DW})}{(\text{TW-DW})} \times 100 \qquad \text{Eqn. 1}$$

Where, FW = fresh weight, DW = dry weight, TW = turgid weight

Chlorophyll Stability Index (CSI)

Two samples with a weight of 250 mg from the same leaf were taken in 2 clean test tubes and 50 mL of distilled water was added in each sample.

One tube was subjected to heat in a water bath at 56 ± 1 °C for exactly 30 min, then leaf samples were taken out from the test tube and macerated with 10 mL of 80% acetone. The other tube was kept as a control. Then the samples were centrifuged at 3000 rpm for 10 min. The supernatant was collected and the volume was made up to 25 mL using 80% acetone. OD was measured at 652 nm in a spectrophotometer (model no. TOPLAB TL 1900UVS, Indian-made). The total chlorophyll content of the treated and untreated (control) samples was calculated by using the following formula.

$$\text{Total chlorophyll} = \frac{\text{OD at 652 x 1000}}{34.5} \times \frac{V}{1000 \times W} \qquad \text{Eqn. 2}$$

Where, W = Weight of the sample taken, V = Volume made up to 25 mL by using 80% acetone.

The chlorophyll stability index is the ratio of the total chlorophyll content of the treated sample to the untreated samples and expressed in percentage (26).

Leaf area duration (LAD)

LAD was worked out by using the following formula (27):

$$\text{LAD} = \frac{\text{LAI 2} + \text{LAI 1}}{2} (t_2 - t_1) \qquad \text{Eqn. 3}$$

LAI 1 = area index at the time (t_1),

LAI 2 = Leaf area index at the time (t_2), (t_2 - t_1) = Time interval in days

Estimation of seed quality parameters

Seed quality parameters were taken at 15 and 30 days after sowing adopting the following formula:

$$\text{Germination percentage (\%)} = \frac{\text{Number of seeds germinated}}{\text{Total number of seeds sown}} \times 100 \qquad \text{Eqn. 4}$$

Ten numbers of seedlings were randomly chosen in all replications at 30 DAS. Root length was calculated by measuring the length from the primary root tip to the collar region and the average root length of 10 plants was expressed in cm. Similarly, from the tip of the true leaves to the collar region was measured for calculating shoot length and the average shoot length was expressed in cm. Dry Matter Production (DMP) was obtained by drying the total plant sample in a shade, followed by drying in a hot air oven at a temperature of 85 ± 2 °C for 48 h and finally followed by cooling of the samples in desiccators with calcium carbonate. The final samples were weighed and expressed in kg ha^{-1}.

The vigour index (VI): VI-I and VI-II values were calculated by the standard method (28) and reported in whole numbers as the vigour index.

VI-I = Germination percentage × Dry matter production

VI-II = Germination percentage × Total length of seedling (cm)

Estimation of fibre quality

High Volume Instrument (HVI) was used to find out fibre length, strength, fineness and uniformity index. Average fibre length (mm) was measured in HVI by weight ratio method. The fibre strength was calculated by dividing the fibre bundle breaking strength by its weight and its unit is tenacity at 1/8" gauge on High Volume Instrument. The fineness of fibre was determined by measuring fibre weight (mg)/unit of fibre length. The uniformity index (%) is obtained by dividing the 50% span length by 2.5% span length (29).

Data on germination percentage, shoot and root length, DMP, VI, plant height, LAD, CSI, RWC, number of monopodial and sympodial branches and bolls $plant^{-1}$, boll weight and yield were recorded replication-wise. Ten numbers of plants at the centre of all plots were tagged to progressive plant sampling throughout the cropping season and average values were taken for calculation.

Gross returns

Gross returns were calculated using seed cotton yield on market price and expressed as $ ha^{-1}.

Net returns

Net returns were worked out by deducting the variable cost of cultivation from gross returns as detailed below and presented in $ ha^{-1}.

Net returns ($ ha^{-1}) = Gross returns ($ ha^{-1}) - variable cost of cultivation ($ ha^{-1})

Benefit-cost ratio

The benefit-cost ratio was calculated based on gross returns and variable cost of cultivation as given below:

$$\text{Benefit - cost ratio (B: C ratio)} = \frac{\text{Gross returns (\$ ha}^{-1}\text{)}}{\text{Cost of cultivation (\$ ha}^{-1}\text{)}} \quad \text{Eqn. 5}$$

Rainfall use efficiency

It is the ratio of the economic product (yield in kg/ha) to the total amount of rainfall utilized for producing that economic product (mm).

Statistical analysis

The data was statistically analyzed at a 5% significance level as recommended (30).

Results

Seed characters

Physiological seed quality parameters *viz.*, germination percentage on 15 and 30 DAS, plant height, DMP and seedling vigour during 30 DAS were maximum in designer seed compared to the seed hardening at 1% KCl. However, treatments failed to influence seed characters significantly. Among different soil and foliar applications of drought mitigation technology, 2.5 kg ha^{-1}of Pusa hydrogel as basal recorded a significantly superior length of root (9.3 cm) and seedling vigour at 30 DAS (Table 1).

Physiological characters

Seed treatment failed to influence plant height, leaf area duration, CSI and RLWC significantly. Among the different soil and foliar application of drought mitigation technology, considerable increase in height of the plant (54.9 and 92.1 cm at 60 and 90 DAS, respectively), CSI during 50 DAS (87.9 %) and RLWC during 50 and 65 DAS (93.5% and 92.5%, respectively) were recorded by spraying of PPFM at 500 mL ha^{-1} at square development, flowering and boll expansion stage (Fig. 1, 3 and 4). The chemical Cycocel applied plot showed stunted growth (Fig. 2).

Soil moisture

Seed treatments *viz.*, seed treatment with 1% KCl and designer seed failed to influence soil moisture significantly. Among the different drought mitigation technologies, Cycocel and Mepiquat chloride sprayed plots recorded higher soil moisture percentages in 15, 30 and 45 cm soil depth during 90 DAS. During this period, crops experienced severe drought due to the early withdrawal of monsoon. The growth retardant sprayed plot recorded 20% higher soil moisture than the control plot (Fig. 5) at 15 and 30 cm soil depth.

Table 1. Impact of drought mitigation methods on physiological as well as seed quality parameters

Treatments	Germination %		30 DAS		DMP at 30 DAS (g)	Vigor of seedling at 30 DAS	
	15 DAS	30 DAS	Root length	Shoot length		Vigour index I	Vigour index II
Seed treatment/ hardening							
M_1-Seed treatment with 1% KCl	80.8	88.2	8.1	13.0	62.9	373.5	1878.8
M_2-Designer cotton seed	82.7	89.5	8.6	13.4	65.7	379.8	1951.3
S Ed	3.0	3.3	0.3	0.5	2.4	14.1	71.1
CD (0.05)	NS	NS	NS	NS	NS	NS	NS
Soil and foliar application							
S_1-Pusa hydrogel at 2.5 kg ha^{-1} as basal	85.5	90.5	9.3	14.2	69.7	415.0	2117.0
S_2-Mepiquat chloride at 250 ppm at 45 and 60 DAS	79.0	88.0	7.5	13.4	64.6	356.5	1830.0
S_3-Cycocel at 250 ppm at 45 and 60 DAS	81.5	87.5	7.6	12.5	64.1	382.5	1750.0
S_4-Cotton plus at 6.25 kg ha^{-1} at flowering and boll development	81.0	88.5	8.9	12.9	62.4	359.0	1924.5
S_5 - PPFM spray at 500 mL ha^{-1} at square formation, flowering and boll development	84.0	88.5	8.3	13.0	62.1	377.5	1875.5
S_6-Control	79.5	90.0	8.8	13.4	63.2	369.5	1993.5
S Ed	5.20	5.70	0.5	0.8	4.1	24.4	123.2
CD (0.05)	NS	NS	1.1	NS	NS	50.6	NS
M X S SEd	7.4	8.1	0.8	1.2	5.8	34.6	174.2
M X S CD (0.05)	NS	NS	NS	NS	NS	71.5	NS

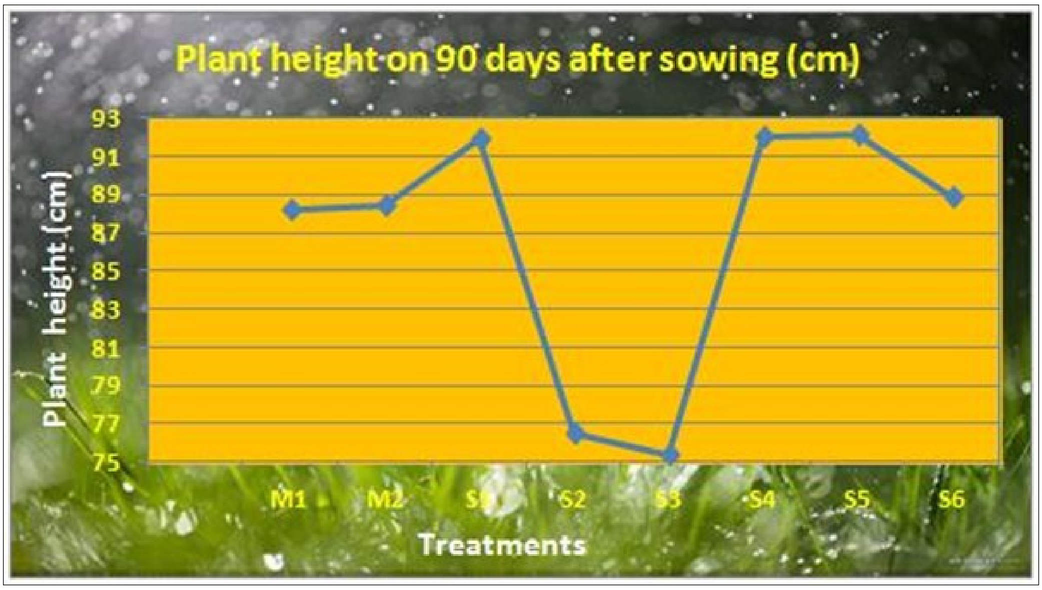

Fig. 1. Impact of drought mitigation methods on cotton plant height.

Fig. 2. Plants showing stunted growth by application of Cycocel which reduces transpiration.

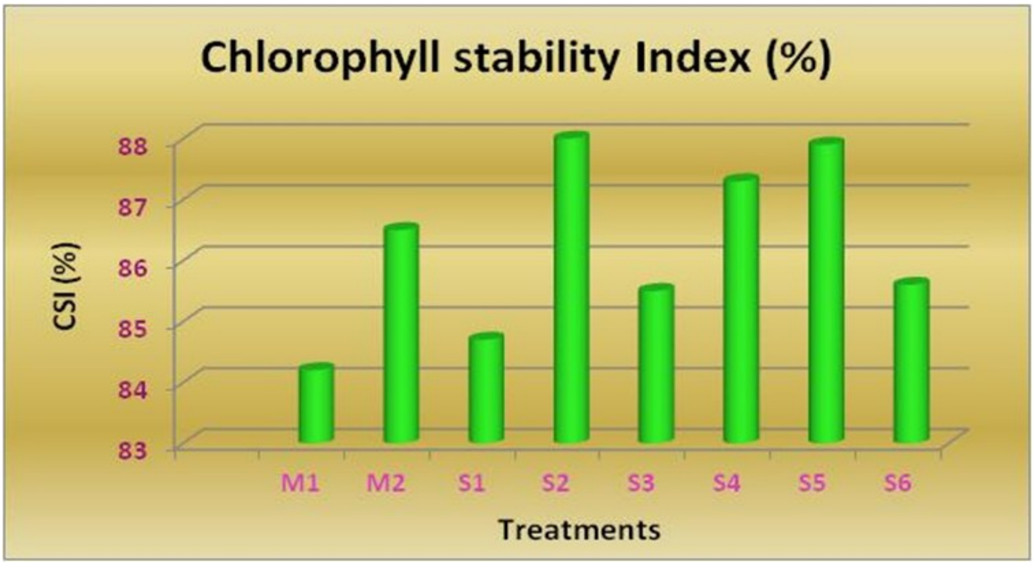

Fig. 3. Impact of drought mitigation methods on cotton chlorophyll stability index.

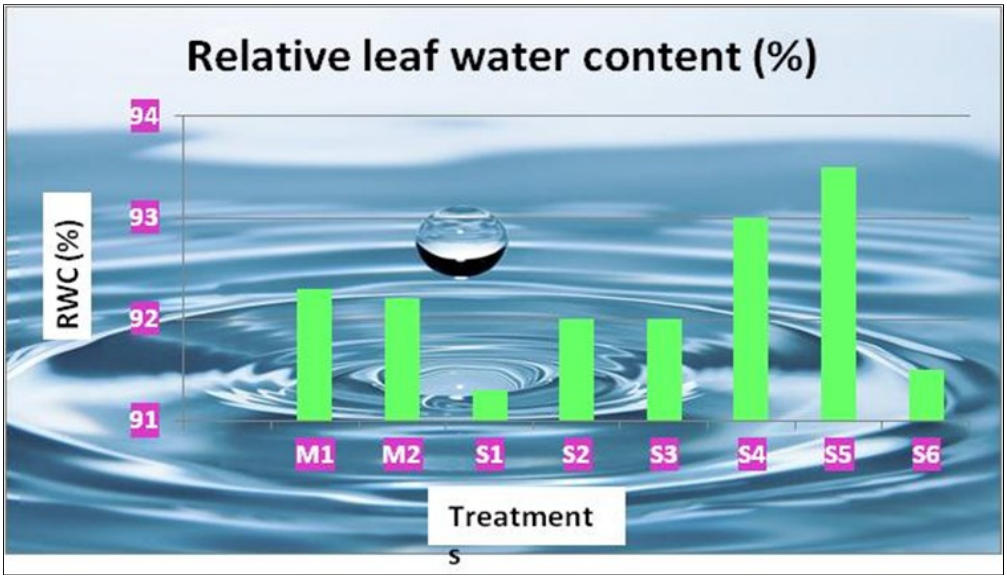

Fig. 4. Impact of drought mitigation methods on cotton RWC on 50 DAS.

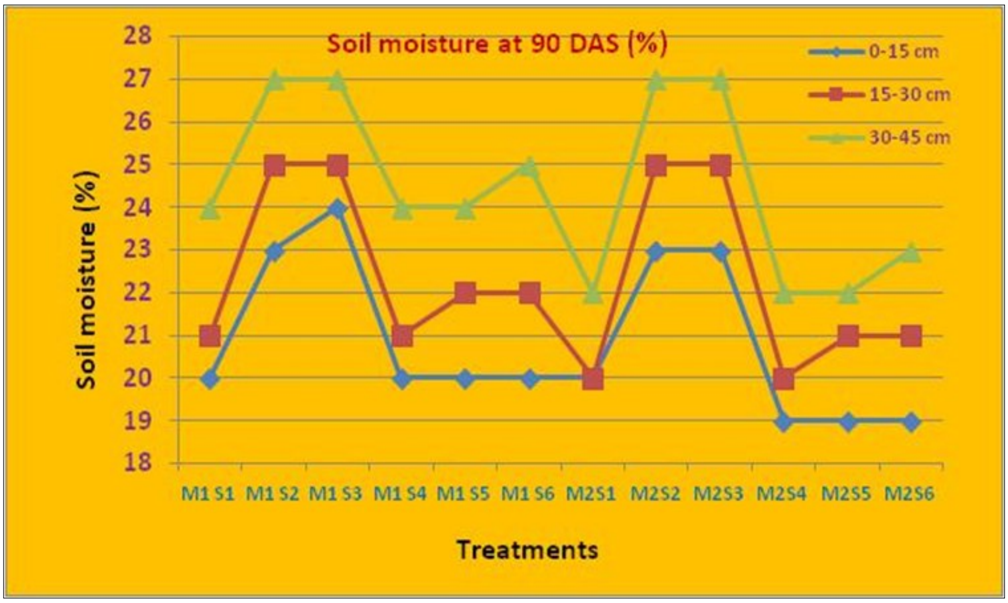

Fig. 5. Soil moisture (%) influenced by various drought mitigation methods on 90 DAS.

Yield parameters

Among the seed treatments, designer seed recorded significantly higher symbodial branches plant^{-1}(10.8 nos.), bolls plant^{-1}(12.1 nos.) as well as boll weight (2.93 g) than the KCl (1%) seed hardening treatment (Fig 7, 8 and 9). Among the various drought mitigation technologies, PPFM spray at 500 mL/ha on square formation, flowering and boll enlargement stage recorded significantly superior symbodial branches (11.1 nos.) and bolls plant^{-1}(13 nos.) and boll weight (3.05 g) and was comparable with a basal application of 2.5 kg ha^{-1} Pusa hydrogel and spraying of Mepiquat chloride at 250 ppm on 45 DAS and 60 DAS, respectively (Fig. 6, 7 and 8).

Yield

Among the seed treatments, designer seed recorded a significantly 12% higher yield of kapas (1210 kg ha^{-1}) compared to KCl (1%) seed hardening treatment (Fig. 9). Among the different soil and foliar application technology, more yield of kapas (1248 kg ha^{-1}) was recorded by PPFM spray at 500 mL/ha during square development, flowering and boll enlargement stage and was comparable with a basal application of 2.5 kg ha^{-1}of Pusa hydrogel (1230 kg ha^{-1}) and Mepiquat chloride at 250 ppm at 45 DAS and 60 DAS, respectively (1215 kg ha^{-1}).

Rainwater Use Efficiency (RUE) and economics

Designer seed sown treatment recorded higher RUE (2.9 kg ha^{-1} mm^{-1}) than KCl (1%) seed hardening treatment. Among the different soil and foliar applications of drought mitigation technology, higher RUE (2.9 kg ha^{-1} mm^{-1}) was recorded by Pusa hydrogel at 2.5 kg/ha as basal, Mepiquat chloride spray at 250 ppm at 45 DAS and 60 DAS and by PPFM spray at 500 mL/ha at square formation, flowering and boll development (Table 2).

Higher total profit ($ 641.5 ha^{-1}), net profit ($ 334.4 ha^{-1}) and rupees per money invested (B:C) (2.09) were registered by the designer seed. Among the different soil and foliar applications of drought mitigation technology, higher total profit (Rs. 661.4 ha^{-1}), net profit (Rs. 360.9 ha^{-1}) and B:C ratio (2.20) was registered by the PPFM spray at 500 mL ha^{-1} during square development, flowering and boll enlargement stage. The next best treatments were basal application of 2.5 kg ha^{-1} of Pusa hydrogel and Mepiquat chloride spray at 250 ppm at 45 DAS and 60 DAS (Table 2).

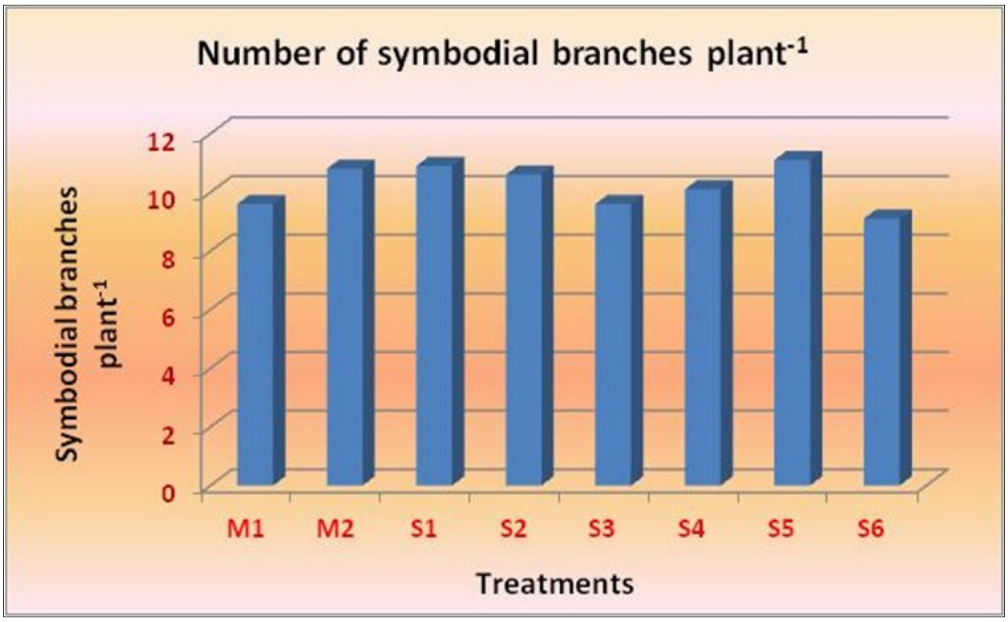

Fig. 6. Impact of drought mitigation methods on symbodial branches (number plant^{-1}).

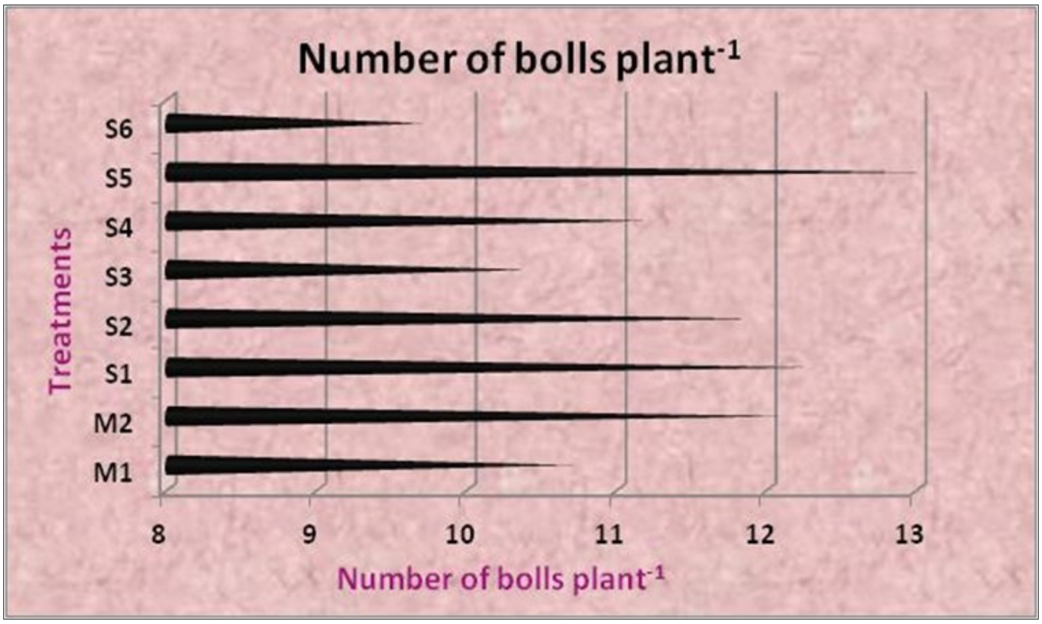

Fig. 7. Impact of drought mitigation methods on number of bolls plant^{-1}.

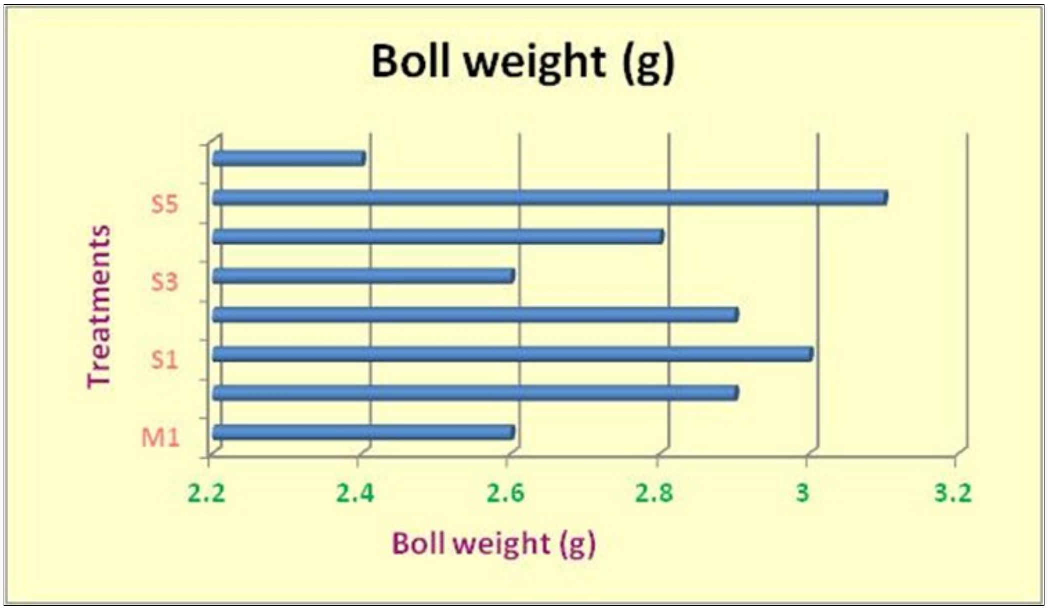

Fig. 8. Boll weight influenced by various drought mitigation methods.

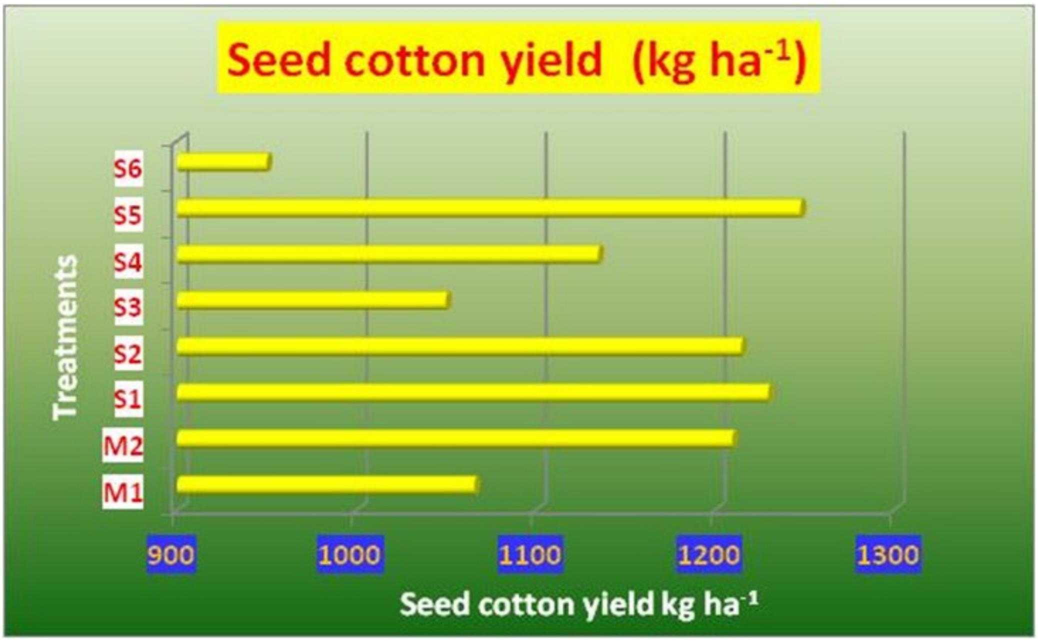

Fig. 9. Impact of drought mitigation methods on seed cotton yield.

Table 2. Effect of drought mitigation methods on fibre quality parameters, rainfall use efficiency and cotton economics

Treatments	Fiber length (mm)	Uniformity index (%)	Fiber strength (g/tex)	Fiber fineness (Micronaire) (Mg/inch)	RUE kg ha^{-1} mm^{-1}	Cost of cultivation \$. ha^{-1}	Gross return \$. ha^{-1}	Net return \$ ha^{-1}	BCR
Factor A: Seed treatment/hardening									
M_1-Seed treatment with 1% KCl	24.3	83.5	25.9	4.59	2.5	303.5	565.1	261.5	1.86
M_2 –Designer cotton seed	25.8	85.0	26.0	4.72	2.9	307.1	641.5	334.4	2.09
SEd	**0.50**	**1.82**	**0.47**	**0.11**	-	-	-	-	-
CD (0.05)	**NS**	**NS**	**NS**	**NS**	-	-	-	-	-
Factor B:Foliar spray									
S_1-Pusa hydrogel at 2.5 kg ha^{-1} as basal	26.7	87.7	26.4	5.32	2.9	350.5	652.1	301.5	1.86
S_2-Mepiquat chloride at 250 ppm at 45 and 60 DAS	26.3	85.2	26.2	5.25	2.9	296.2	644.1	347.8	2.17
S_3-Cycocel at 250 ppm at 45 and 60 DAS	24.6	79.6	24.8	4.53	2.5	296.2	556.65	260.4	1.88
S_4-Cotton plus at 6.25 kg ha^{-1} at flowering and boll development	26.0	84.5	25.7	4.76	2.7	307.5	601.7	294.2	1.96
S_5 - PPFM spray at 500 mL ha^{-1} at square formation, flowering and boll development	26.9	87.9	28.3	5.61	2.9	300.5	661.4	360.9	2.20
S_6- Control (No foliar application)	23.1	78.7	24.4	4.29	2.2	281.0	503.7	222.6	1.79
SEd	**1.17**	**3.01**	**0.90**	**0.18**	-	-	-	-	-
CD (0.05)	**NS**	**NS**	**NS**	**0.37**	-	-	-	-	-
SEd	**1.94**	**5.25**	**1.54**	**0.31**	-	-	-	-	--
CD (0.05)	**NS**	**NS**	**NS**	**NS**	-	-	-	-	-

Fiber quality parameters

There is no significant difference in fibre quality parameters *viz.*, fibre length and strength as well as uniformity index due to seed treatments and foliar application. Even though, fibre length (16%), fibre strength (16%) and uniformity index (12%) was higher in all the treatments than in control and fiber fineness was significantly higher for foliar treatments (31%) over control.

Discussion

More than 50% of crop yield is severely affected by environmental stress like drought. Seed treatments did not express a significant effect on germination percentage, plant height, dry matter production (DMP) and seedling vigour at 30 days after sowing (DAS), leaf area duration, CSI and RWC may be attributed to the dual treatments comprising seed treatments with 1% potassium chloride (KCl) and the designer seed subjected to the identical 1% KCl seed hardening protocol prior to sowing. This approach potentially augments the plant's drought resistance during periods of water deficit, as potassium application enhances stomatal conductance, fortifies root systems and elevates the water and osmotic potential of the plant during hydric stress through improved water uptake (31, 32). Seed hardening along with 2.5 kg ha^{-1} Pusa hydrogel registered higher physiological seed quality characters. It might be due to hardened seeds induced drought resistance during the early stage of seedlings and Hydrogel application increased the soil moisture retention as reported with blackgram and *Corymbia citriodora* (20, 33). Many researchers found that Hydrogel application increased soil aeration, fertilizer and water retention, meanwhile, evapotranspiration was reduced improving the emergence of various crop seedlings (34, 35).

Spraying of PPFM at 500 mL ha^{-1} at square formation, flowering and boll enlargement phenophases recorded a significant increase in the plant height, CSI and RWC. This can be attributed to the induced PPFM synthesize of a variety of metabolites including phytohormones promoting plant growth and yield (36). PPFM has the capability to modify physiological characteristics *viz*., root differentiation, branching, vigour of seedling, heat and cold tolerance (37).

Growth retardants like Mepiquat chloride and Cycocel sprayed at 250 ppm at 45 and 60 DAS recorded 42% higher soil moisture than control due to short and compact plant nature with lower leaf area, less reproductive branches (38) and with reduced evapo-transpiration loss of water. Gibberellic acid production has been inhibited by growth retardants responsible for the elongation of cells (39, 40). Hence plants turn into more compact habits with deep green foliage (Fig. 2) and short stature showing extended post-harvest life (Fig. 2) (41).

Designer seeds recorded 12.5, 13, 11.5 and 12 percentages higher symbodial branches and bolls per plant, weight of boll and yield of cotton over 1% KCl alone treated plot. Higher chlorophyll content leads to more photosynthate production which increases the photosynthetic efficiency of treated plants (7). Crop experiences late season drought due to early withdrawal of monsoon during the cropping period. The reproductive phase is the important stage which can be easily affected by abiotic stress in all crops. Frequent drought during the reproductive phase affects the plants with immediate and long-term effects (42). Drought-induced high-temperature stress changes the plant morphology, biochemical aspects and plant physiology which results in reduced plant growth and development. High temperatures due to drought during the reproductive stage induced early flowering and bud initiation with an increase in flower drop in all plants (43). Spraying of PPFM at 500 mL/ha at square development, flowering and boll enlargement stages recorded 22, 34, 29 and 31 percentages of higher symbodial branches and bolls per plant; the weight of boll and yield over control. PPFM has the ability to improve the activity of the catalase enzyme which saves the plants from abiotic stress situations, thereby increasing the stress-tolerant index (44) and also relative water content promoting drought-bearing ability (20). The increase in plant chlorophyll content (20, 45, 46) increased photosynthesis which in turn improved the yield of the crop.

The employment of designer seeds, coupled with the application of Pusa hydrogel, as well as the spraying of Mepiquat chloride and PPFM, resulted in elevated rainfall use efficiency, attributable to the superior yields recorded in these treated plots. Higher RUE due to the application of Pusa hydrogel, PPFM along with the formation of broad bed furrow was also reported in Blackgram (20). A markedly higher percentage of total gross income (13.5%), net income (28%) and benefit-cost ratio (12%) were observed with designer seed cotton in comparison to the 1% potassium chloride seed hardening treatment. This advantage is likely due to the enhancements in the physical properties of seeds through seed designing, which provide protection from biological adversaries (47) via the incorporation of inoculants, protectants, nutrients and polymer coatings in the designer seed formulation. Protectant-coated seeds control pest and disease attacks therefore, the growth of plants and dry matter production was higher which increased the availability of more photosynthates to sink and finally yield increased (7) and reduced the cost of cultivation by decreasing pest and disease problems. With respect to drought mitigation technology higher percentage of gross (total) return (31%), net income (return) (62%) and B:C values (23%) were found in the treatment of PPFM spray at 500 mL/ha during square formation, flowering and boll enlargement phases due to increased yield than control. This result of higher net income by application of PPFM was confirmed by other researchers (20).

Treatments failed to influence the fibre quality of cotton except for fibre fineness. Though non-significant, the PPFM spray at 500 mL/ha at square formation, flowering and boll development enhanced cotton fibre quality over control. Micronaire was recorded higher in PPFM spray. The experiments conducted by various researchers also reported similar findings (48-50).

The enhanced efficacy of seeds treated with KCl may be attributed to the osmotic advantage conferred by K^+, which facilitates improved cellular water saturation and its role as a co-factor in essential biological processes, such as the maintenance of ionic equilibrium within cells and its binding to the enzyme pyruvate kinase, which is critical for respiration and the metabolism of carbohydrates (51, 52). Biologically active products that incorporate live strains of *Azospirillum* contribute to the enhancement of plant growth through mechanisms such as biological nitrogen fixation, phosphate mobilization, and the augmentation of nutrient absorption. *Trichoderma* spp. are recognized as endophytic symbionts of plants that are extensively utilized as seed treatment agents to mitigate diseases and promote plant growth and yield. The application of these fungi as seed treatments is common, as they have the potential to enhance plant establishment and induce sustained improvements in overall plant quality (53). The observed increase in yield may be attributed to the augmented efficiency of photosynthesis, which occurs via the stabilization of chlorophyll, leading to a heightened production of photosynthates and consequently, an increased translocation of organic materials from the source to the sink. Similar experiments were conducted by various researchers on cotton (54, 55), rice (56), blackgram (57), sunflower hybrid (58) and tomato (59).

Foliar application of methanol or plant growth-promoting rhizobacteria (PPFMs) has been demonstrated to enhance the populations of PPFMs, which subsequently leads to an elevated concentration of cytokinin produced by bacteria and this increased cytokinin concentration has been associated with improved yields in cotton and sugarcane (60). Gibberellic acid (GA3), recognized as a plant growth regulator, serves as a crucial growth modulator affecting processes such as cellular division and tissue differentiation, net assimilation rates, accumulation of dry matter, leaf expansion and elongation, regulation of transpiration rates, as well as influencing flowering and photosynthetic activity (61, 62). In addition to these roles, GA is integral in modulating plant growth and development in response to various abiotic stressors (63).

The application of PPFM in isolation was observed to enhance growth parameters such as the number of leaves per plant and chlorophyll content, alongside yield attributes including the number of pods per plant in snap bean cultivation. Furthermore, there was a significant increase in total sugars, ascorbic acid, amino acids and protein content within the pods (64).

A considerable segment of the population that depends on rainfed agricultural methodologies demonstrates a notable vulnerability to both transient dry conditions and extended drought occurrences. The potential risk exposure to such adversities may lead to a reluctance to commit resources to agricultural inputs that have the potential to improve crop yields. Moreover, the changing precipitation patterns linked to climate change are likely to intensify this challenge for many smallholder farmers. The higher cost of Pusa hydrogel usage under rainfed conditions is not possible for the subsistence farming community. This situation underscores the urgent need for adaptive strategies to mitigate the impacts of climatic variations on agricultural practices.

Planning and managing agricultural operations in rainfed areas effectively requires thorough knowledge of soil and climate conditions that are prevalent in that particular area. Crop choice, water management and total production in rainfed agriculture are all greatly impacted by soil properties and climate. In order to increase water infiltration and lower the risk of drought, soil conservation techniques assist shields the soil from erosion. The key factor in lowering cultivation costs will be low-cost technologies such as crop residue, biochar application and broad bed furrows. Research on this topic will raise farmers' standards of living.

Conclusion

From the present study, it is recommendable that sowing of designer cotton seed along with PPFM spray at 500 mL/ha at square, flowering and boll enlargement stages is effective for getting higher yield and profit in cotton under dryland situations.

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Authors' contributions

SS participated in the design of the study and conducted experiments, studied agronomic parameters, VB carried out seed quality parameters study. SA, SA and RK drafted the manuscript. SP and SA performed statistical analysis. KMP conceived the study and participated in its design and coordination. RS corrected the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

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