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Research Paper

Evaluating *in-situ* moisture-conservation measures with soil conditioner (PUSA hydrogel) on soil moisture fluctuations and productivity of cotton (*Gossypium hirstum*) under rainfed Vertisols

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ABSTRACT

A field experiment was conducted at Aruppukottai, Tamil Nadu during *rabi* season of 2016–17 and 2017–18 to study the impact of *in-situ* moisture-conservation and stress-management practices on soil-moisture retention and productivity of 'SVPR 2' cotton (*Gossypium hirsutum* L.) under rainfed Vertisols. The experiment was laid out in a split-plot design, replicated thrice. The main-plot treatments, consisted of different *in-situ* moisture-conservation measures viz. broad bed and furrows (I_1), ridges and furrows (I_2) and compartmental bunding (I_3). The sub-plot comprised with stress-management practices, viz. soil application of PUSA hydrogel @ 5 kg/ha (S_1), soil application of PUSA hydrogel @ 5 kg/ha + foliar spray of 1% KCl (S_2), soil application of PUSA hydrogel @ 5 kg /ha + foliar spray of 5% Kaolin (S_3), soil application of PUSA hydrogel @ 5 kg/ha + foliar spray of PPFM @ 500 ml/ha (S_4), soil application of PUSA hydrogel @ 5 kg/ha + foliar spray of salicylic acid 100 ppm (S_5) and the control (S_6). Data analysis of 30 years rainfall was done for the probability occurrence of dry spell in particular standard weeks by the Markov chain method. The results of this study showed that treatment combination of broad bed and furrows and soil application of PUSA hydrogel @ 5 kg/ha + foliar spray of PPFM @ 500 ml/ha resulted in significantly higher soil-moisture content at various depth of 0–15, 15–30 and 30–45 cm and seed-cotton yield 1,580 kg/ha (2016) and 1,943 kg/ha (2017).

Key words : Broad bed and furrows, moisture fluctuations, *In-situ* water harvesting, PUSA hydrogel, Rainfed cotton

India ranks first in area with 11.88 million ha, accounting 30% of world acreage and 22% (35.1 million bales of lint) of the world cotton production with a lint productivity of 568 kg/ha (DCD, 2017). Nearly 65% of the cotton crop is cultivated under rainfed condition in the country. In Tamil Nadu, 0.133 million ha is under cotton cultivation with production of 0.65 million bales, with lint productivity of 620 kg/ha. India is becoming one of the largest exporters of cotton shipping 6.9 million bales (2015–16) followed by the USA (Kannan *et al.*, 2017).

Water stress is one of the most important factors limiting crop productivity and adversely affects square and boll formation, lint yield and fibre quality of cotton. The loss of productivity due to the lack of rainfall and insufficient frequency in irrigation has threatened cotton farming. Rainfed areas can be made productive and profitable by adopting improved technologies for rainwater conservation and harvesting and commensurate agricultural production technologies. Soil-management practices are tailored to store and conserve as much rainfall as possible by reducing runoff and increasing storage capacity of soil profile. The most efficient and economic way of conserving rainfall is to hold it *in-situ.* The principle behind the *in-situ* moisture-conservation practices is to increase the infiltration by reducing the rate of runoff, temporarily impounding the water on the surface of the soil to increase the opportunity time for infiltration and modifying the land configuration for inter-plot water harvesting (Muthamilselvan *et al.*, 2006).

The moisture stress during crop-growth period is the primary cause for the yield reduction in cotton. To improve the soil-moisture availability, by reducing the evaporation losses and retaining the moisture in effective rooting zone. Soil application of superabsorbent polymers (SAPs) is

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found to be the promising methodology in rainfed areas. However, very limited research work has been done on this aspect. One of such developed product is 'PUSA hydrogel' which is first successful an indigenous semi-synthetic superabsorbent technology for conserving water and enhancing crop productivity and thereby increases the water-use efficiency (IARI, 2012). To reduce transpiration losses, foliar application of nutrient formulations, growth regulators, antitranspirants etc. on cotton are being tried by many researchers. Keeping this in view, an attempt was made to study the impact of *in-situ* moisture-conservation measures with soil conditioner (PUSA hydrogel) on soil-moisture fluctuations and productivity of cotton under rainfed Vertisols

MATERIALS AND METHODS

A field experiment was conducted at Regional Research Station, Tamil Nadu Agricultural University, Aruppukottai, during the winter (*rabi*) season of 2016–17 and 2017–18 with the test variety 'SVPR 2'. The experimental site comes under the Southern agro-climatic zone of Tamil Nadu and geographically situated at 9º33' N and 78º 05' E, 50 m above mean sea-level. North-East monsoon season is found to be more favourable in Aruppukottai region since 42% of annual rainfall is being received during this monsoon season. The soil was medium deep, well-drained and Vertisols (Type Chromusterts). The soil was low in available nitrogen, low in available phosphorus and high available potassium. All package of practices were carried out as per recommendation of (TNAU, 2020).

The experiment was laid out in a split-plot design, replicated thrice. The main plot treatments consisted of different *in-situ* moisture-conservation measures, viz. broad bed and furrows (I_1), ridges and furrows (I_2) and compartmental bunding (I_3). The sub-plot comprised stress-management practices, namely soil application of PUSA hydrogel @ 5 kg/ha (S_1), soil application of PUSA hydrogel @ 5 kg/ha + foliar spray of 1% KCl (S_2), soil application of PUSA hydrogel @ 5 kg/ha + foliar spray of 5% Kaolin (S_3), Soil application of PUSA hydrogel @ 5 kg/ha + foliar spray of PPFM @ 500 ml /ha (S_4), soil application of PUSA hydrogel @ 5 kg/ha + foliar spray of salicylic acid 100 ppm (S_5) and the control (S_6).

Cultural operations other than the treatments were done as per the recommended practices of the *TNAU Crop Production Guide, 2012*. The experimental field was prepared with necessary primary and secondary tillage operations to bring the soil to required level of tilth. At the start of the experiment, the field was ploughed once with disc plough followed by 2 cultivator ploughings at optimum moisture. Then rotavator was used to break the clods and the field was levelled properly. Land-management practices were carried out in the respective plots as per the treatment schedule.

Broad bed furrow were prepared with bed size of 120 cm and furrow size of 30 cm having depth of 15 cm on either side with a gradient of 0.8% using the tractor-drawn broad bed furrow former. Ridges and furrows were formed at 45 cm spacing by using the tractor-drawn ridge plough. Small bunds of 15 cm width and 15 cm height were made in both directions (across and along the slope), to divide the field into small compartments by using manual labour with spade.

Healthy and viable seeds of cotton variety 'SVPR 2' were sown @ 20 kg /ha after delinting with concentrated sulphuric acid @ 100 ml/kg seed. Seeds were hand-dibbled 2 seeds/hill at 45 cm spacing between row and 15 cm between plants. Seeds were also sown separately in polybags, which were used for gap-filling at 15 days after sowing. A recommended fertilizer dose of 40:20:40 kg N : P : K/ha were applied in the form of urea (46% N), single superphosphate (16% P_2O_5) and muriate of potash (60% K_2O). Entire dose of phosphorus, 50% of N and K were applied as basal. Remaining N and K was applied in 2 splits– at the time of square initiation (45 DAS), and peak flowering (75 DAS).

The desired amount of hydrogel (5 kg/ha) was mixed with dry and fine sand of less than 0.25 mm size in 1 : 10 ratio, in order to distribute uniformly along the row. Sand-mixed hydrogel was applied in line where seed was sown (Narjary *et al.*, 2013).

Calculated quantity of foliar solution was sprayed in the respective treatment plots using hand-operated knapsack sprayer fitted with fan-type WFN 40 nozzle by controlled droplet-application method at moisture stress. Required quantity each of 10 g KCl, 50g Kaolin and 100mg salicyclic acid was dissolved in 1 litre of water seplarately and their spray solutions were prepared at the time of sowing. The required quantity of 500 ml pink pigmented facultative methylobacteria (PPFM) was dissolved in 500 litres water and spray solution was prepared at the time of spray.

Data analysed for the probability occurrence of 30 years rainfall in a standard week showed that there is a possibility occurrence of getting more than 80% of consecutive dry spell is laid with 45th and 50th standard weeks. So, to avoid stress foliar spray was given at 45th and 50th standard weeks in 2016 and 2017 based on historical rainfall probability analysis by Markov chain method to fix foliar spray application during the experimentation period

Soil moisture at 15 days interval was estimated at 0–15, 15–30 and 30–45 cm soil depths through oven-drying method. Soil sample was collected in a moisture can and wet weight of sample was recorded. The soil sample were dried in hot-air oven at 105°C until constant weight was obtained and dry weight of the sample was recorded and expressed in percentage. Moisture content of soil sample was estimated using the formula,

$$\text{Moisture content (on weight basis)} = \frac{\text{Wet weight–Dry-weight}}{\text{Dry weight}} \times 100$$

Under dryland situation, evaluation of effective rainfall would provide the stock of soil- moisture available for the present and future utilization by the crop plants raised. Based on this, effective rainfall was calculated through indirect method as suggested by Gupta *et al.* (1972). Potential evapo-transpiration (PET) was calculated based on pan-evaporation method and necessary stage wise crop coefficient (Kc) value of cotton crop was used to compute consumptive use of cotton raised in the present investigation. Based on the value obtained from the computation, effective rainfall and daily moisture balance were arrived.

To calculate PET, the formula suggested by Penman (1948) was used.

$$ETo = Kp \times Epan$$

where, ETo, Reference evapotranspiration (mm/day); Kp, pan co-efficient (0.8); and Epan, pan evaporation (mm/day).

Crop evapotranspiration was estimated as:

$$ETc = Kc \times ETo$$

where, ETc, Crop evapotranspiration (mm/day); Kc, crop co-efficient; and ETo, potential evapotranspiration (mm/day)

Cotton Kc values for different stages as suggested by FAO are given below.

Stages	Days	Kc value
Initial	20	0.40
Crop development	35	0.80
Mid-season	40	1.15
Late season	30	0.70

Soil water balance was computed using the method suggested by Gupta *et al.* (1972).

$$Wn = Wn - 1 + RFn - ETn$$

Where, Wn, Soil water on n^{th} day; Wn-1, previous day soil water; RFn, rainfall on n^{th} day; and

ETn, evapotranspiration on n^{th} day.

Effective rainfall was calculated as the difference between rainfall and water loss through runoff.

$$ERn = RFn - Sn$$

where, ERn, Effective rainfall; RFn, rainfall on n^{th} day; and Sn, water loss (The rainfall received after the soil profile saturation was considered as ineffective and accounted for water loss).

From the fully opened bolls, the seed cotton was harvested in 4 pickings. The busted bolls in the 2 border rows on all the sides were harvested first before each picking. The net plot was harvested separately. The harvested seed cotton was shade-dried and weighed. The seed-cotton yield was obtained from net plot area was shade-dried, weighed at each picking and yields of all pickings were added and calculated as kg per plot and then expressed in kilogram per hectare. The data obtained were subjected to statistical analysis and were tested at 5% level of significance to interpret the treatment differences as suggested by (Gomez and Gomez, 1984).

RESULTS AND DISCUSSION

Weather conditions and performance of cotton

Like most of the agricultural crops, cotton production and productivity under rainfed eco-system is highly influenced by moisture availability.

The meteorological data revealed that the weather parameters prevailed throughout the cropping period were favourable for better growth and yield of cotton. North-East monsoon season is found to be more favourable in Aruppukottai region since 42% of annual rainfall is being received during this monsoon season.

In the present field experimentation, during the cropping period of winter (*rabi*) 2016, a total rainfall of 283 mm (Table 1) was received in 12 rainy days. Out of this, 62.0, 147.4, 58.4 and 15.2 mm rainfall was received in seedling stage, early squaring, boll development and maturity stage respectively. From this distribution, it was found that the rainfall received during the cropping period was not well distributed to entire crop-growth period, especially at reproductive stages of crop and accounted that 30% of deviation from the normal seasonal rainfall of 383.2 mm. Further, the first year of experimentation (2016) was characterized by high atmospheric water demand due to uneven distribution of rainfall and thus results in poor setting of squares and bolls which finally resulted with reduced seed-cotton yield.

In contrast, during the cropping period in 2017, the amount of rainfall received during cropping season was 313.6 mm (Table 1) in 19 rainy days. Out of this, 135.4, 132.6, 42 and 3.6 mm rainfall was received in seedling stage, early squaring, boll development and maturity stage respectively. Cotton raised during 2017 exhibited significantly higher growth and yield attributes as compared to 2016. This may be owing to 2017 experienced 10% high rainfall as compared to 2016. The rainfall received during the cropping period was very well distributed in the entire crop-growth period, especially at vegetative and reproductive stages of crop and thus better distribution of rainfall had favoured the growth and resulted in higher seed-cotton yield.

Hence, the influence of rainfall on crop growth was gained paramount importance under rainfed condition. Moisture stress in cotton restricts both vegetative and fruit growth. Response of cotton to moisture stress varies with the growth stage of the crop, the degree and length of stress (Thakare *et al.*, 2014).

Table 1. Water balance studies of rainfed cotton

Component	2016	2017
Evaporation (mm)	698.5	638.6
Crop evapotranspiration (mm)	446.4	403.0
Potential evapotranspiration (mm)	698.5	510.9
Rainfall (mm)	283.0	313.6
Effective Rainfall (mm)	170.7	202.2
Surplus (mm)	112.4	111.4

Weekly mean maximum and minimum temperatures in 2017 (33.2 ºC and 20.9 ºC) were found to be lower than of 2016 (33.9 ºC and 22.5 ºC). This means fluctuations in day and night air temperatures were narrower in 2017 which might have helped the crop to grow better. Sankaranarayanan *et al.* (2010) anticipated 40 to 50% less biomass in cotton at 20/10 °C and 40/30 °C, respectively, with optimum temperature of 30/20°C. Other parameters like relative humidity, sunshine and pan evaporation were favourable for better crop growth throughout seasons in both the years.

Water-balance

By computation of soil water balance, the moisture availability at different stages of crop growth was taken into account. The moisture viability was found to be higher during 2017–18 than 2016–17 in the experimental site.

A total rainfall of 283.0 mm was received during the cropping period of 2016–17. Out of this, 170.7 mm was found to be effective rainfall with water surplus of 112.4 mm (Table 1). With respect to pan evaporation (PE), crop evapotranspiration (ETc), potential evapotranspiration (PET) recorded 698.5, 446.4 and 698.5 mm during cropping period respectively. The difference in water was attributed due to difference in effective rainfall and the rainfall available for the consumptive use of the crop. This was again substantiated by the intensity of rainfall in 2016–17 wherein 50.2 mm and 82.8 mm were received in 2 rainy days accounting for high surplus and low effective rainfall obtained by more surface runoff.

Similarly during 2017–18 cropping period, total rainfall of 313.6 mm was received during cropping period. Out of this, 202.2 mm was found to be effective rainfall with a water surplus of 111.4 mm (Table 1). During the period, 638.6, 403.0 and 510.9 mm of water was recorded, respectively, for pan evaporation (PE), crop evapotranspiration (ETc) and potential evapotranspiration (PET).

Soil-moisture content

Data on soil-moisture content estimated from 15 days after sowing (DAS) to 120 DAS at 15 days intervals under 0–15, 15–30 and 30–45 cm soil depth during both the years revealed that, the soil-moisture content increased with the

Table 2. Effect of *in-situ* moisture-conservation and stress-management practices on plant height (cm), dry-matter production (kg/ha) and leaf-area index of rainfed cotton (pooled data of winter season of 2016 and 2017)

Treatment	Plant height (cm)	Dry-matter production (kg/ha)	Leaf-area index
In-situ moisture conservation			
Broad bed and furrows	135.1	5,353	5.08
Ridges and furrows	127.9	4,984	4.72
Compartmental bunding	120.4	4,603	4.35
SEm±	2.3	89	0.14
CD (P=0.05)	4.1	184	0.27
Stress-management practices			
Soil application of PUSA hydrogel @ 5 kg/ha	119.2	4,646	4.37
Soil application of PUSA hydrogel @ 5 kg/ha + foliar spray of 1% KCl	136.3	5,307	5.00
Soil application of PUSA hydrogel @ 5 kg/ha + foliar spray of 5% Kaolin	132.5	5,150	4.67
Soil application of PUSA hydrogel @ 5 kg/ha + foliar spray of PPFM @ 500 ml/ha	142.5	5,500	5.54
Soil application of PUSA hydrogel @ 5 kg/ha + foliar spray of salicylic acid 100 ppm	126.8	4,904	4.58
Control	110.5	4,372	4.13
SEm±	2.3	89	0.14
CD (P=0.05)	4.1	184	0.27

PPFM, Pink, Pigmented Facultative Methylotrophs increase in soil depth. In all the treatments, subsurface depth of 30–45 cm showed higher soil-moisture content than 15–30 and 0–15 cm. Various *in-situ* moisture-conservation measures and stress-management practices exerted significant influence on the soil-moisture content. The crop experienced more than 7 weeks of dry spell with continuous dry spell during 45–47th and 50th standard weeks with in the cropping period. These dry weeks matched rainfall probability analysis by Markov chain method in both years.

Among the *in-situ* moisture-conservation measures, at 15, 30 and 45 cm depth, broad bed and furrow (I_1) recorded-highest soil-moisture content, was followed by ridges and furrows (I_2) in all growth stages. Compartmental bunding CB (I_3) registered the lowest percentage of soil moisture at all growth stages in both years (Fig. 1 and 2).

The soil application PUSA hydrogel improved the soil moisture content. Soil-application of PUSA hydrogel @ 5 kg/ha resulted in significantly the highest soil moisture per cent at the depth of 0–15, 15–30 and 30–45 cm during 2016 and 2017. More soil moisture was retained under soil application of PUSA hydrogel @ 5 kg/ha up to 60 DAS and thereafter the soil-moisture content decreased gradually. The control plot (S_6) exhibited the lowest soil moisture at all growth stages in both years. There was no significant interaction between *in-situ* moisture conservation-measures and stress-management practices.

Adequate soil moisture is the key to successful crop production in dryland areas. Land configuration is the mechanical measure for better *in-situ* moisture conservation, as the soil profile acts as reservoir for moisture storage. In the present study, soil-moisture content increased with increase in soil depth. At all the treatments, sub surface depth of 30–45 cm showed higher soil-moisture content than 15–30 and 0–15 cm. Higher moisture content of 30% was recorded at 30–45 cm depth, which was owing to higher moisture depletion in the top layers. This shows maximum root activity in the top 0–15 cm, causing more absorption of soil moisture. Under rainfed condition, if enough soil moisture is retained at subsurface (root zone), crop can utilize the available moisture for its growth and also surface evaporation loss can be minimized. Devaranavadgi Vivek and Santhana Bosu (2014) also reported similar.

The crop experienced with the dry spell during 45–47th standard weeks followed by 50th standard week and in total more than 7 weeks during cropping period matched the probability analysis by Markov chain method for both the years.

Among the *in-situ* moisture-conservation, higher soil-moisture content was retained in broad bed and furrow system. At all the stages of crop growth, broad bed and furrow system recorded higher moisture content at all soil depths, viz. 0–15, 15–30 and 30–45 cm, followed by ridges and furrows, which low moisture content was observed in compartmental bunding. This might be attributed better collection of rainwater in the furrows and absorption and retention of rainwater due to horizontal movement of water from furrows to the inner layer of broad bed and furrow (BBF). This type of enrichment of moisture could help maintain the soil-moisture content, better crop growth and

Table 3. Effect of *in-situ* moisture-conservation and stress-management practices on sympodia/plant, boll weight (g/boll), bolls/plant and seed-cotton yield (kg/ha) of rainfed cotton (pooled data winter season of 2016 and 2017)

Treatment	Sympodia/ plant	Boll weight (g/boll)	Bolls/ plant	Seed-cotton yield (kg/ha)
In-situ moisture conservation				
Broad bed and furrows	13.0	3.76	18.1	1,590
Ridges and furrows	11.9	3.53	15.8	1,467
Compartmental bunding	10.9	3.36	13.5	1,350
SEm±	0.2	0.10	0.6	32
CD (P=0.05)	0.5	0.24	1.6	117
Stress-management practices				
Soil application of PUSA hydrogel @ 5 kg/ha	11.3	3.42	13.7	1,376
Soil application of PUSA hydrogel @ 5 kg/ha + foliar spray of 1% KCl	12.4	3.71	19.0	1,580
Soil application of PUSA hydrogel @ 5 kg/ha + foliar spray of 5% Kaolin	12.2	3.50	16.7	1,485
Soil application of PUSA hydrogel @ 5 kg/ha + foliar spray of PPFM @ 500 ml/ha	13.2	3.85	20.8	1786
Soil application of PUSA hydrogel @ 5 kg/ha + foliar spray of salicylic acid 100 ppm	12.0	3.48	15.2	1,476
Control		3.31	9.4	1,109
SEm±	0.3	0.11	0.6	48
CD (P=0.05)	0.6	0.16	1.2	100

PPFM, Pink, Pigmented Facultative Methylotrophs yield in BBF. Our results close confirm the findings of Muthamilselvan *et al*. (2006), NICRA (2013) and Kuotsu *et al.* (2014).

This soil-moisture build up owing to BBF practices helped in providing favourable environment for plant growth and responded to applied nutrients. Nyamadzawo *et al.* (2013) also reported similar results.

From the present study, it was also found that soil application PUSA hydrogel significantly improved the soil-moisture availability than control. Soil application of PUSA hydrogel @ 5 kg/ha resulted in significantly higher soil-moisture per cent at the depth of 0–15, 15–30 and 30–45 cm (Fig. 1 and 2). This might be owing to the fact that, the application of polymers buffer root zone with water by reducing the water loss from deep percolation and beneficial to the plant roots to grow and proliferate into soil profile and helps for sustaining crop growth and development. Application of hydrogel improves water-retention capacity of soils and available water supplies to the crop. Water absorption by hydrogel was rapid and the highest which increased the moisture retention linearly. Hence, the polymer allows water to infiltrate into the soil beyond its point of application. More soil moisture was retained under soil application of PUSA hydrogel @ 5 kg/ha upto 60 DAS, and after that soil-moisture content started decreasing gradually, due to absorption of moisture by the crops from hydrogel polymer. The super-absorbent polymers (SAPs) have special properties because of their 3-dimensional structure. They are cross-linked macromolecules with segments of hydrophilic groups that can absorb and retain liquids and the absorbed water and release it slowly.These stored water in the SAPs are released slowly as required by the crop to improve growth under limited water supply (Yazdani *et al.*, 2007). Similar findings were also reported by Rehman *et al.* (2011).

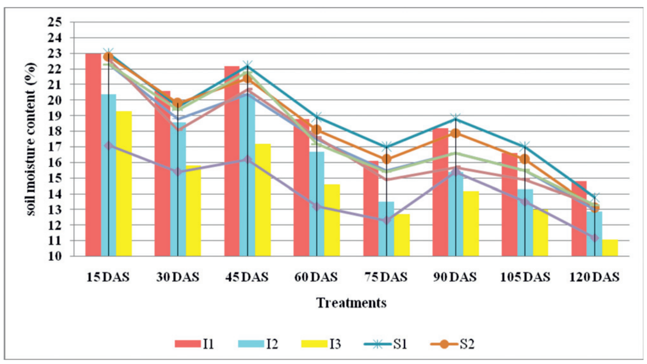

Fig. 1. Effect of *in-situ* moisture-conservation and stress-management practices on soil-moisture content (%) at 0–15 cm depth of rainfed cotton at 15 days interval (15, 30, 45, 60, 75, 90, 105 and 120 days after sowing) during the winter season of 2016 (details of treatments are given under Materials and Methods)

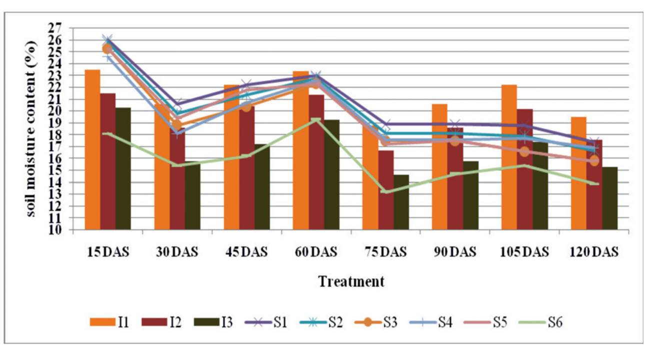

Fig. 2. Effect of *in-situ* moisture-conservation and stress-management practices on soil-moisture content (%) at 0–15 cm depth of rainfed cotton at 15 days interval (15, 30, 45, 60, 75, 90, 105 and 120 days after sowing) during the winter season of 2017 (details of treatments are given under Materials and Methods)

Rainwater-use efficiency

Rainwater-use efficiency (RWUE) measured the extent to which rainwater was utilized. Among the *in-situ* moisture-conservation treatments, the BBF system registered higher RWUE than compartmental bunding (Table 4). This might be attributed due to the better collection of rainwater in the furrows and absorption with retention of rainwater in the broadbed and furrows with the help of horizontal movement of water from furrows to the inner layer of BBF during dry period (Karam *et al.*, 2009).

Stress-management practices recorded higher RWUE than the control. Soil application of PUSA hydrogel @ 5 kg/ha + foliar spray of PPFM @ 500 ml/ha showed marked influence with higher RWUE in cotton than the other management practices. The application of SAPs improves the physical properties of soil and water-use efficiency, reduce infiltration rate to deeper layers, increases water-holding capacity and decreases the evaporation losses (Shooshtarian *et al.*, 2012). The hydrogel polymers led to increase the rainwater-use efficiency since water that would have otherwise leached beyond the root zone is captured and effectively utilized. When polymers are incorporated into the soil, it is presumed that they retain large quantities of water, which are released as required by the plant.

Growth

Among the different land configurations, plant height, leaf-area index (LAI) and dry-matter (DMP) production were higher under broad bed furrows, followed by ridges and furrows and compartmental bunding (Table 2). At all stages of crop growth, the increased in plant height and higher LAI paved the way for production photosyntheates under BBF, followed by ridges and furrows and compartmental bunding during both the years. This was possibly owing to better soil-moisture availability to the crop at all growth stages. The favourable soil-moisture availability under this treatment favoured higher NPK uptake, which in turn reflected in increased plant height and LAI.

With respect to stress-management practices, soil application of PUSA hydrogel @ 5 kg/ha + foliar spray of PPFM @ 500 ml ha^{-1} recorded significantly higher taller plants, LAI and DMP respectively. As the water content of the plant decreases, cell shrinks and turgour pressure increases against cell wall relaxes. This decrease in cell volume resulting from lower turgour pressure subsequently concentrates solutes in cells. Superabsorbent polymers (SAPs) increased the turgour pressure inside the cells by maintaining sufficient amount of water as per plant need and thus causing increase in leaf area and other related parameters as reported by Yazdani *et al.* (2007). In addition to that, the foliar application of PPFM helped in more leaf expansion, plant height and high biomass, which led the increased LAI in this treatment. This is in accordance with the findings of Madhaiyan *et al.* (2006).

Yield attributes

The number of sympodial branches/plant, bolls/plant and boll weight were found significantly higher with BBF than the other treatments (Table 3). Owing to increased and continuous availability of soil moisture under broad bed and furrows system, the growth was enhanced which resulted increase of the number of sympodial branches. Boll production and their retention in the plant are controlled by soil-moisture conditions. Early energy translocation to the reproductive parts under higher moisture supply may be the reason for the increased boll production under BBF. This might also be ascribed to higher retention of moisture boll at development stage and better aeration in rooting zone. This leads to production of more numbers of bolls. Kuotsu *et al.* (2014) also reported similar findings.

Among the stress-management practices, soil application of PUSA hydrogel @ 5 kg/ha + foliar spray of PPFM @ 500 ml/ha recorded higher number of sympodial branches/plant, bolls/plant and boll weight over the control**.** This might be owing to application of superabsorbent polymers that helped alleviate drought stress through retention of more moisture in the rooting zone and increased the number and weight of bolls. Further, foliar application of PPFM, increased total dry matter production owing better translocation of photosyntheates and led to better boll development and boll weight. These results are in conformity with observations made by Madhaiyan *et al.* (2006).

Seed-cotton yield

Yield is contributed by different yield components and any influence made by extraneous factor, will alter the yield significantly. In the present study, increased seed-cotton yield could be attributed to better crop growth and yield components because of consistent soil-moisture availability combined influence of BBF, soil conditioner and foliar application of PPFM (Table 3). The BBF recorded significantly higher seed cotton yield of 1,246 (2016) and 1,590 kg/ha (2017), which was 23% (2016) and 19% (2017) higher than the compartmental bunding. Increment in seed-cotton yield was owing to more soil-moisture availability at the root zone which favoured better crop growth. This coupled with higher stomatal conductance and transpiration rate resulted accumulation of more dry-matter and

Table 4. Effect of *in-situ* moisture–conservation and stress-management practices on rainwater-use efficiency and water use efficiency (kg/ha mm) of rainfed cotton (pooled data of winter seasons of 2016 and 2017)

Treatment	Rainwater-use efficiency	Water use efficiency (kg/ha mm)
In-situ moisture conservation		
Broad bed and furrows	5.12	3.99
Ridges and furrows	4.59	3.57
Compartmental bunding	4.30	3.35
SEm±	0.12	0.06
CD (P=0.05)	0.27	0.14
Stress-management practices		
Soil application of PUSA hydrogel @ 5 kg/ha	4.35	3.38
Soil application of PUSA hydrogel @ 5 kg/ha + foliar spray of 1% KCl	5.09	3.96
Soil application of PUSA hydrogel @ 5 kg/ha + foliar spray of 5% Kaolin	4.74	3.69
Soil application of PUSA hydrogel @ 5 kg/ha + foliar spray of PPFM @ 500 ml/ha	5.70	4.43
Soil application of PUSA hydrogel @ 5 kg/ha + foliar spray of salicylic acid 100 ppm	4.62	3.59
Control	3.54	2.75
SEm±	0.09	0.07
CD (P=0.05)	0.18	0.15

Crop: cotton Period: 1984–2014 Limit: 20 mm

Standard week	Initial probabilities		Conditional probabilities			
	P (W)	P (D)	P (W/W)	P (D/W)	P (D/D)	P (W/D)
1.	0.1000	0.9000	0.0000	1.0000	0.8889	0.1111
2.	0.0645	0.9355	0.3333	0.6667	0.9643	0.0357
3.	0.0645	0.9355	0.0000	1.0000	0.9310	0.0690
4.	0.0323	0.9677	0.0000	1.0000	0.9655	0.0345
5.	0.0323	0.9677	0.0000	1.0000	0.9667	0.0333
6.	0.0000	1.0000	0.0000	1.0000	1.0000	0.0000
7.	0.0323	0.9677	0.0000	0.0000	0.9677	0.0323
8.	0.1290	0.8710	0.0000	1.0000	0.8667	0.1333
9.	0.0323	0.9677	0.0000	1.0000	0.9630	0.0370
10.	0.0323	0.9677	0.0000	1.0000	0.9667	0.0333
11.	0.1290	0.8710	0.0000	1.0000	0.8667	0.1333
12.	0.0645	0.9355	0.5000	0.5000	1.0000	0.0000
13.	0.0645	0.9355	0.0000	1.0000	0.9310	0.0690
14.	0.2903	0.7097	0.5000	0.5000	0.7241	0.2759
15.	0.2903	0.7097	0.1111	0.8889	0.6364	0.3636
16.	0.2258	0.7742	0.1111	0.8889	0.7273	0.2727
17.	0.2258	0.7742	0.0000	1.0000	0.7083	0.2917
18.	0.3548	0.6452	0.1429	0.8571	0.5833	0.4167
19.	0.3226	0.6774	0.3636	0.6364	0.7000	0.3000
20.	0.2258	0.7742	0.1000	0.9000	0.7143	0.2857
21.	0.2903	0.7097	0.8571	0.8571	0.6667	0.3333
22.	0.1935	0.8065	0.0000	1.0000	0.7273	0.2727
23.	0.1613	0.8387	0.0000	1.0000	0.8000	0.2000
24.	0.0968	0.9032	0.0000	1.0000	0.8846	0.1154
25.	0.0323	0.9677	0.0000	1.0000	0.9643	0.0357
26.	0.0968	0.9032	0.0000	1.0000	0.9000	0.1000
27.	0.1935	0.8065	0.3333	0.6667	0.8214	0.1786
28.	0.0968	0.9032	0.1667	0.8333	0.9200	0.0800
29.	0.1290	0.8710	0.0000	1.0000	0.1429	0.1429
30.	0.1290	0.8710	0.2500	0.7500	0.8889	0.1111
31.	0.0968	0.9032	0.0000	1.0000	0.8889	0.1111
32.	0.1613	0.8387	0.0000	1.0000	0.8214	0.1786
33.	0.1935	0.8065	0.0000	1.0000	0.7692	0.2308
34.	0.2903	0.7097	0.3333	0.6667	0.7200	0.2800
35.	0.3226	0.6774	0.4444	0.5556	0.7273	0.2727
36.	0.2903	0.7097	0.4000	0.6000	0.7619	0.2381
37.	0.3871	0.6129	0.3333	0.6667	0.5909	0.4091
38.	0.3226	0.6774	0.4167	0.5833	0.7368	0.2632
39.	0.4194	0.5806	0.6000	0.4000	0.6667	0.3333
40.	0.4516	0.5484	0.4615	0.5385	0.5556	0.4444
41.	0.4839	0.5161	0.5000	0.5000	0.5294	0.4706
42.	0.6452	0.3548	0.7333	0.2667	0.4375	0.5625
43.	0.6129	0.3871	0.7500	0.2500	0.6364	0.3636
44.	0.6774	0.3226	0.7895	0.2105	0.5000	0.5000
45.	0.6774	0.5806	0.7143	0.2857	0.8000	0.6000
46.	0.4194	0.3226	0.5238	0.4762	0.4000	0.2000
47.	0.3871	0.6129	0.3077	0.6923	0.5556	0.4444
48.	0.2258	0.7742	0.3333	0.6667	0.8421	0.1579
49.	0.2581	0.7419	0.5714	0.4286	0.8333	0.1667
50.	0.1935	0.8065	0.3750	0.6250	0.8696	0.1304
51.	0.1613	0.8387	0.1667	0.8333	0.8400	0.1600

The crop experienced with the dry spell during 45–47th standard weeks, followed by 50th standard week and in total more than 7 weeks during cropping period matched the probability analysis by Markov chain method for both years.
Initial and conditional probabilities of rainfall (Markov chain probability)

yield components and ultimately the seed-cotton yield. This is in similarity with the findings of Muralidaran and Solaimalai (2005). Higher seed-cotton yield was realized with complementary alliance of *in-situ* moisture- conservation measures with stress-management practices in the present study. Significant influence by stress management practices also recorded with soil application of PUSA hydrogel @ 5 kg /ha + foliar spray of PPFM @ 500 ml /ha, which registered higher seed-cotton yield.

The increased seed-cotton yield under soil application of PUSA hydrogel @ 5 kg/ha + foliar spray of PPFM @ 500 ml/ha was 60% during 2016 and 61% during 2017 over the control. This may be owing to the increase in growth and yield-related attributes. Further, it could be because of sufficient availability of soil moisture because of super absorbent polymer under water stress condition, which in turn resulted to better translocation of water, nutrients and photo-assimilates and finally better plant development. El-Hady *et al.* (1981) and Sivapalan (2001) also reported similar findings under water-stress condition. However during stress, presence of the photosynthetically active leaf area due to moisture availability of superabsorbent polymers (SAP) exhibited more chlorophyll meter readings, was also positively correlated to yield. Similar findings were reported by Johnkutty and Palaniappan (1995). The present study revealed that foliar application of PPFM when combined with soil application of PUSA hydrogel resulted in enhanced seed-cotton yield. The enhancement of yield was associated with increased number of bolls/plant through improved boll retention. When cotton plants having adequate environmental conditions to grow which allowed the plants to gain more plant height and number of bolls, thus giving more seed-cotton yield, as also reported by Bozbek *et al*. (2006) and Bange *et al*. (2008). Dhale *et al.* (2010) significant increase in seed-cotton yield with the application of PPFM. The beneficial influence by PPFM may be attributed to several factors such as, release of growth-promoting substances like auxins, particularly indole-3-acetic acid (IAA) and indole-3-pyruvic acid, zeatin, zeatin riboside, proliferation of beneficial organisms in the phyllosphere and reacted cytokinins by methylotrophs enhanced the plant growth which attributed to increase in the yield of a crop. And hence, it could be concluded that foliar application of PPFM favourably influenced the seed-cotton yield. In addition, PPFM spray boosted the plant water status and enhanced the chlorophyll content in plants. Further, the gibberellic acid produced by PPFM, might have increased the chlorophyll content, photosynthetic activity by enhancing the number of stomata and stomatal conductance.

The combination of BBF with soil application of PUSA hydrogel @ 5 kg/ha + foliar spray of PPFM @ 500 ml /ha recorded higher yield, increase being 133 and 150% during 2016 and 2017, respectively, than the compartmental bunding. This may be owing to the favourable environment provided by the *in-situ* moisture-conservation and stress-management practices, which enhanced the growth and yield-attributing characters of cotton during both the years.

Economics

Higher net income of ₹31,250/ha in 2016 and 49,400/ha in 2017 was realized under treatment combination of BBF with soil application of PUSA hydrogel @ 5 kg/ha + foliar spray of PPFM @ 500 ml/ha, with higher benefit: cost (B: C) ratio of 1.65 (2016) and 2.03 (2017). The lowest net returns of 581 in 2016 and 3,943/ha in 2017 and B: C ratio of 1.01 in 2016 and 1.25 in 2017 was obtained in treatment combination of compartmental bunding with the control. Profound influence of *in-situ* moisture-conservation and stress-management practices resulted in better crop growth. Higher seed-cotton yield realized might be the reason for improving higher net income and B: C ratio under BBF with soil application of PUSA hydrogel @ 5 kg/ha + foliar spray of PPFM @ 500 ml/ha. Further, the higher cost of production owing to application of super absorbent polymer can be compensated by attaining the highest yield. The present study exhibited the advantage of using treatment combination of BBF with soil application of PUSA hydrogel + foliar spray of PPFM towards successful maintenance of crop under moisture-stress condition and fetching higher benefit: cost ratio indicating it economic feasibility in adopting technology.

Thus, adoption of broad bed and furrows system combined with soil application PUSA hydrogel enhanced the soil moisture availability and recorded significantly higher soil-moisture per cent at 0–15, 15–30 and 30–45 cm soil depths than the other treatments. The higher values indicate that the moisture conservation and stress-management practices improve growth rate which leads more yield potential of rainfed cotton. Broad bed and furrows combined with soil application of PUSA hydrogel @ 5 kg/ha + foliar spray of PPFM @ 500 ml/ha during the stress period was found to be the best agronomic management practice to conserve soil moisture, enhance yield and economic returns in cotton under rainfed Vertisols.

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