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Effect of plant bioregulators on growth, yield and water production functions of sorghum [*Sorghum bicolor* (L.) Moench]

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ABSTRACT

Use of plant bioregulators has been shown to mitigate the impacts of water stress and benefit crops under water scarce conditions. Therefore, a field experiment was conducted to evaluate the interactive effects of plant bioregulators (PBR's) and supplemental irrigation on growth and grain yield of sorghum [*Sorghum bicolor* (L.) Moench]. Exogenous application of PBR's included: 10 μM salicylic acid (SA), 100 mg L^{-1} sodium benzoate (SB), 500 ppm thiourea (TU), 1.5% potassium nitrate (KNO_3) at seedling elongation (20 DAS), reproductive (50 DAS) and panicle emergence (75 DAS) stages and control (no spray of PBR). Line source sprinkler system (LSS) was used to apply variable quantities of irrigation water (IW) i.e. equalling 0.95, 0.80, 0.65, 0.50, 0.35, 0.20 and 0.05 times the CPE (cumulative open pan evaporation). The maximum grain yield (3.60–3.88 Mg ha^{-1}) was obtained at IW: CPE 0.80 and declined @ 0.43–0.49 Mg ha^{-1} for every 0.1 IW: CPE for PBR's and the corresponding values were 3.49 and 0.53 Mg ha^{-1} without PBR. The application of PBR's mitigated water stress and improved gain yield by 6.8–18.5%. SA was more effective under moderate (IW: CPE 0.79–0.50) while SB and TU were better under severe water deficits (IW: CPE 0.49–0.05). PBR's maintained higher leaf water content, lower canopy temperature, modulated the stomatal opening and ultimately the source–sink relations thereby improving the yield and water productivity under deficit irrigation. The maxima of water productivity varied between 1.16–1.41 kg m^{-3} with PBR's while it was 1.12 kg m^{-3} without PBR and the latter could be achieved with 25.2–49.7% lesser irrigation water (IW) with PBR's. It is concluded that PBR's like SB and TU present viable option for improving sorghum yield and water productivity under the conditions of deficit irrigation.

1. Introduction

Besides having a high yield potential, sorghum [*Sorghum bicolor* (L.) Moench] is known for high drought, heat and salinity tolerance. Therefore, it has become a major staple food and multifunctional crop for the arid and semi–arid tropics across the world. India contributes about 16% of the world sorghum production and is mainly grown both during and post–monsoon seasons for food grains and fodder (Dhanoji, 2010). The superior quality, larger and lustrous grains of the post rainy crop fetches higher market price for the farmers. However, being cultivated mostly as rainfed crop, its growth and productivity is mainly hampered by water deficits. The carried over soil moisture is insufficient to meet crop demands while the rainfall is erratic that generally lead to midseason droughts to impact pollen viability, seed-setting and ultimately seed yield (Prasad et al., 2006). Therefore, supplemental irrigation is considered to be the key strategy to unlock its yield potential. In fact substantial improvements have been reported even with limited irrigation (Tolk and Howell, 2008). Farre and Faci (2006) reported a high ability of sorghum to extract water from deeper soil layers under moderate or severe water deficits. Thus, understanding the effect of water stress on crop performance under receding moisture situation seems essential for planning irrigation strategies. Since line source sprinkler system produces a continuous and decreasing gradient of applied water, these have been extensively used to develop crop water production functions (Sezen and Yazar, 2006; Tekin et al., 2014). Hence, the first objective of the study was to develop water production functions of sorghum grown in semi-arid part of Deccan Plateau of India.

The beneficial role of PBR's in enhancing the crop yields through the regulation of physiological processes and plant–water relations has recently been elaborated through several reports (Khan et al.,

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2015; Srivastava et al., 2016; Wakchaure et al., 2016). Though the most of PBR's have been tried under pot or controlled conditions, those reported for their viability include salicylic acid (Fayez and Bazaid, 2014); sodium benzoate (Beltrano et al., 1999; Kumar et al., 2014); thiourea (Bhunia et al., 2015; Wakchaure et al., 2016) and potassium nitrate (Gimeno et al., 2014). Nevertheless, there is general lack of information on the relative responses of PBR's under field conditions (Wakchaure et al., 2016). So, the other objective was to evaluate the effectiveness of selected PBR's on yield and water productivity of sorghum under variable water deficits.

2. Material and methods

2.1. Experimental site and treatment details

A field experiment was conducted at the research farm of the ICAR–National Institute of Abiotic Stress Management, Baramati (18°09′N, 74°30′E and 560 MAMSL), during the winter seasons of 2014–15 and 2015–16. The experimental site falls under the agro–climatic region, Western Maharashtra Scarcity Zone (MH–6) and is highly susceptible to drought and characterized by low and erratic rainfall. The annual rainfall is 584 mm which is mainly restricted to south–west (71%) and retreating (21%) monsoon (Minhas et al., 2015). The weather parameters as recorded during crop growth are given in Table 1. The black soil of the experimental field is sandy clay in texture (sand, silt and clay, 56.2, 8.0, 35.8%, respectively), its pH (1: 2.5 soil: water suspension) is 8.3; EC 0.24 dS m^{-1}; organic matter 6.4 g kg^{-1}; available N, P and K 173, 20 and 145 kg ha^{-1}, respectively. Its moisture constants are 0.33 and 0.15 g g^{-1} at 0.033 and 1.5 MPa suction, respectively. Irrigation water as supplied from the nearby Nira left canal had pH 7.6 and EC 0.26 dSm^{-1}.

The field experiment, laid out in a split plot design with four replications, consisted of (i) foliar application of PBR's namely salicylic acid (SA; 10 μM), sodium benzoate (SB; 100 mg L^{-1}), thiourea (TU; 500 ppm) and potassium nitrate (KNO_3; 15 g L^{-1}) at seedling elongation (20 DAS), reproductive (50 DAS) and panicle emergence stage (75 DAS) along with control (no PBR) as main plot treatments and (ii) seven levels of irrigation (subplot treatments) based upon the climatological approach i.e. ratio of depth of water applied (IW) and cumulative USWB (United States Weather Bureau) class A open pan evaporation (CPE). These were IW: CPE 0.95, 0.80, 0.65, 0.50, 0.35, 0.20 and 0.05 and were maintained using line source system (LSS) with eight sprinklers spaced at 6.1 m which provides linearly decreasing water distribution pattern at 30 m wetted diameter operated at 300 kPa pressure. Maximum water delivered near the main lateral was 19 mm h^{-1} and the least was 0.4–0.7 mm h^{-1} at a radius of 15 m. The details of the set up have earlier been given by Wakchaure et al. (2016). The usable experimental area (30 m × 30 m) was divided into main plots (14 m × 2.25 m) along the LSS and further each main plot was divided into subplots (2.25 m × 2 m) as shown in Fig. 1. Irrigation water applied was measured using PVC catchment cans (100 mm dia., 195 mm height) installed across the centre of subplots. The details of quantities of irrigation water applied during the two years are given in Table 2. Total 15 L solution was prepared using irrigation water with selected concentration of each PBR's and sprayed on the next day (11.00–13.30 h) of irrigation. Sorghum (*cv.* Phule Suchitra) was drilled @ 8 kg ha^{-1} in rows (45 cm apart) perpendicular to main lateral of LSS using seed–cum–fertiliser drill. The sowing dates were October 5 and 4 during 2014 and 2015 and the crop was harvested on February 4 and 1 in 2015 and 2016, respectively. A post–plant irrigation of 5.1 cm was applied to facilitate the germination during 2014 while such an irrigation was not required due to sufficient residual soil moisture and a rainfall event (3.38 cm) during 2015. Half the recommended N (40 kg) and total P (40 kg P_2O_5) was applied as basal dose while rest half of N was top dressed at 35 days after sowing (DAS).

2.2. Growth, canopy and physiological parameters

Plant height, LAI, canopy air temperature difference (CATD) and chlorophyll content (SPAD) were monitored at interval of 15 days. Various phenological stages like seed elongation (20–45 DAS), reproductive (50–60 DAS), panicle emergence (70–75 DAS) and grain development stages (90–95 DAS) were defined by 50% of the plants reaching that stage. Leaf area index (LAI) was measured using portable leaf area meter (AccuPAR PAR/LAI Ceptometer, LP–80, Decagon Devices, Inc. WA). CATD interpreted from the relative water status in plant and computed using portable gas exchange fluorescence system (GFS–3000, Germany). Also chlorophyll content was measured using portable chlorophyll meter (SPAD–502 plus, Konika Minolta Optics, Inc., Japan).

2.3. Sorghum yield attributes

The stalk yield and grain attributes from each subplot were measured after manual harvesting of sorghum at physiological maturity. The plant height at maturity, panicle size (sphericity index, SI) and grain weight (g)/panicle were measured from the randomly selected 10 plants for each subplot. Sphericity index (SI), the degree of sphericity (Φ) of panicle was calculated using the expression given by Mohsenin (1970). The 1000 grain weight (test weight) was expressed in grams (g) at 14% moisture content. The harvested plant samples were placed in hot air oven and dried to constant weight at 60 °C for obtaining the stalk yield. Harvest index (HI) was determined as the ratio of grain yield to total above ground biomass at maturity.

2.4. Statistical analysis

The statistical analysis of data and derived variables from the experiment was performed using PROC GLM procedure in SAS software package (Ver. 9.3). The statistical significance among main and subplot treatments effects in each year and over two years was estimated by individual and pooled analysis of variance. Student's *t* test was performed to determine the least significant differences (LSD) at 5% level of probability for the comparison of means.

3. Results and discussion

3.1. Interactive response of irrigation and PBR's on grain and stalk yield

Both the grain and stalk yields were affected by the irrigation levels and exogenous application of PBR's (Tables 3 and 4). The overall yields were comparatively higher during the year 2014–15 than that obtained during the year 2015–16. This was obviously due to warmer and moist weather conditions during vegetative phase and relatively cooler and dryer weather conditions in grain development stage those were conducive for better growth and productivity. Prasad et al. (2006) and Bandyopadhyay et al. (2014) have earlier reported that congenial climatic conditions greatly enhances grain and biomass yields of crop.

When averaged for the two years, the grain yield decreased from 3.68 to 0.49 Mg ha^{-1} with reduction in irrigation water supplies from IW: CPE 0.95–0.05, though the yield could be sustained until IW: CPE 0.65. The maximum grain yield (3.60–3.88 Mg ha^{-1}) was obtained at IW: CPE 0.80 with PBR's against the 3.51 Mg ha^{-1} without PBR and the latter was obtained at IW: CPE 0.95. The relative yields (RY), considering latter (3.51 Mg ha^{-1}) as reference, obtained

Table 1
Weather parameters (maximum (T_{max}) and minimum (T_{min}) temperature, rainfall, cumulative open pan evaporation (CPE), relative humidity (RH), sunshine) during cropping period of the sorghum.

Growing period	2014–2015						2015–2016					
	T_{max} (°C)	T_{min} (°C)	Rainfall (mm)	CPE (mm)	Mean RH (%)	Sunshine (h)	T_{max} (°C)	T_{min} (°C)	Rainfall (mm)	CPE (mm)	Mean RH (%)	Sunshine (h)
October	31.7	19.2	25.7	136.7	60.7	6.8	33.1	20.3	33.8	146.6	58.8	7.7
November	30.2	16.3	44.0	132.5	60.9	7.4	31.6	17.4	4.6	159.5	53.7	7.3
December	28.4	11.8	7.6	112.7	61.1	8.3	31.2	14.1	0.0	142.5	55.1	8.1
January	28.3	12.0	0.1	119.6	60.7	7.7	30.1	11.8	0.0	142.3	51.4	8.1
February	30.8	13.1	0.0	20.3	53.6	9.8	34.0	15.0	0.0	6.0	45.5	9.3
Mean/Total	29.9	14.5	77.4	521.7	59.4	8.0	32.0	15.7	38.4	596.8	52.9	8.1

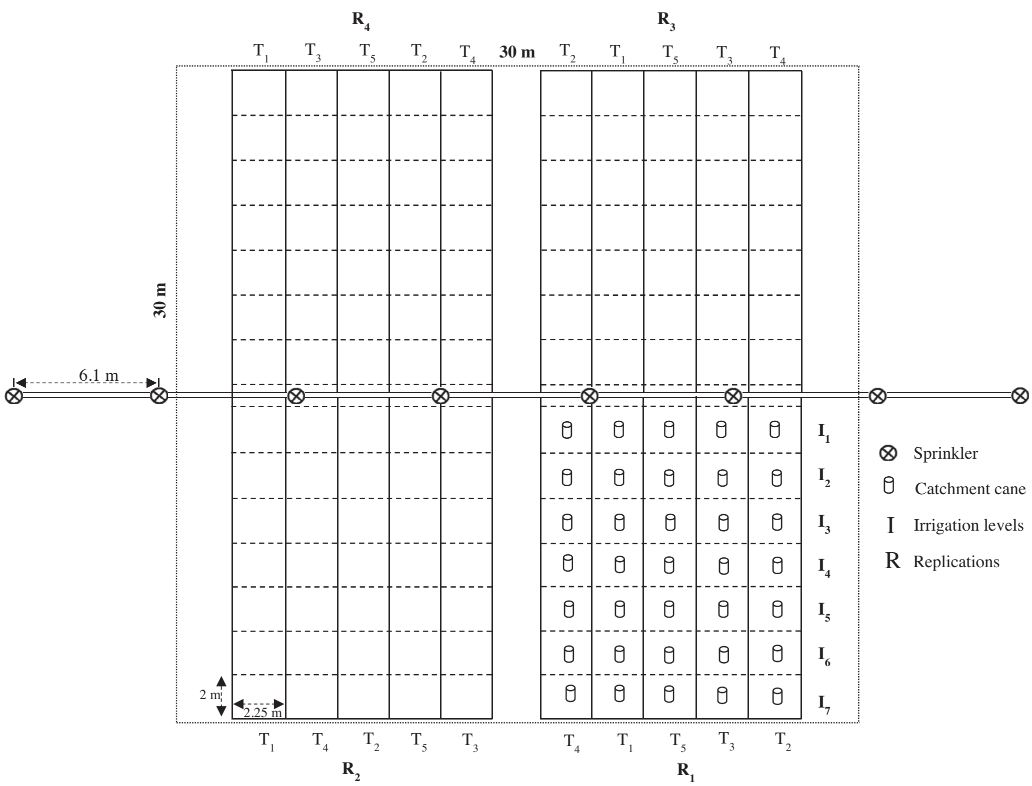

Fig. 1. Layout of line source sprinkler system (T_1–T_5 denote SA, SB, TU, KNO_3 and no PBR, respectively).

Table 2
Irrigation water applied (cm) and days of irrigation under different irrigation levels.

IW: CPE	Irrigation applied with LSS		Total water (LSS+ CI[a] + RF[b])	
	2014–15	2015–16	2014–15[a+b]	2015–16[b]
0.95	25.4	39.2	38.2	42.6
0.80	20.3	31.3	33.1	34.7
0.65	16.5	25.5	29.3	28.8
0.50	12.7	19.6	25.5	23.0
0.35	8.9	13.7	21.7	17.1
0.20	5.1	7.8	17.9	11.2
0.05	1.3	2.0	14.2	5.3
Irrigation (DAS)	14, 28, 39, 67, 83	14, 26, 38, 50, 68, 85		

LSS represents amount of irrigation water applied using line source sprinkler system.
[a] CI (5.1 cm) represents the amount of common irrigation applied at time of sowing during 2014–2015.
[b] RF represents total amount of rainfall received in 2014–15 was 7.74 cm during sorghum growth period and that in 2015–16 was 3.38 cm received just after sowing represents no need of CI.

without PBR were 0.99, 0.93, 0.73, 0.46, 0.21 and 0.07 at IW: CPE 0.80, 0.65, 0.50, 0.35, 0.20, 0.05, respectively. The similar trends in grain yield of sorghum with increased water deficits have been reported by Farre and Faci (2006).

The crop responded to application of PBR's especially under water deficit conditions. When compared with maximum yield ($3.73\,Mg\,ha^{-1}$) obtained with PBR's at IW: CPE 0.80, RY obtained were 0.97, 0.84, 0.59, 0.33 and 0.15 at IW: CPE of 0.65, 0.50, 0.35, 0.20 and 0.05, respectively. With overall improvement of 18.5% in grain yield compared with no PBR, SA was most effective and this was followed by SB, TU, KNO_3 where yield enhancements were 17.2, 13.7 and 6.8%, respectively. Grain yield obtained with TU was

Table 3
Grain yield of sorghum as affected by the plant bioregulators and irrigation levels.

Plant bioregulators (PBR's)	Grain yield (Mg ha^{-1}) with irrigation level (IW: CPE)							
	0.95	0.80	0.65	0.50	0.35	0.20	0.05	Mean
2014–2015								
SA	3.75	4.00	4.12	3.80	2.63	1.70	0.72	2.96
SB	3.71	3.89	4.09	3.60	2.60	1.72	1.02	2.94
TU	3.66	3.80	3.86	3.50	2.46	1.56	0.74	2.80
KNO_3	3.66	3.70	3.71	3.25	2.25	1.08	0.47	2.59
No PBR	3.57	3.60	3.64	3.01	1.98	0.90	0.32	2.43
Mean	3.67	3.80	3.89	3.43	2.38	1.39	0.65	2.74
LSD($p = 0.05$)	PBR 0.118 IW: CPE 0.103 PBR × IW: CPE 0.231							
2015–2016								
SA	3.62	3.76	3.57	3.08	1.89	0.98	0.27	2.45
SB	3.58	3.61	3.38	2.71	1.90	1.05	0.52	2.39
TU	3.56	3.60	3.25	2.60	1.78	1.00	0.49	2.32
KNO_3	3.54	3.49	3.05	2.40	1.49	0.82	0.24	2.15
No PBR	3.45	3.37	2.91	2.11	1.27	0.59	0.15	1.98
Mean	3.55	3.56	3.23	2.58	1.67	0.89	0.33	2.26
LSD($p = 0.05$)	PBR 0.127 IW: CPE 0.125 PBR × IW: CPE 0.279							
Pooled (2014–2015 and 2015–2016)								
SA	3.68	3.88	3.85	3.44	2.26	1.34	0.50	2.71
SB	3.65	3.75	3.73	3.16	2.59	1.38	0.77	2.67
TU	3.61	3.70	3.56	3.05	2.12	1.28	0.62	2.56
KNO_3	3.60	3.60	3.38	2.83	1.87	0.95	0.36	2.37
No PBR	3.51	3.49	3.27	2.56	1.63	0.75	0.24	2.21
Mean	3.61	3.68	3.56	3.01	2.03	1.14	0.49	2.50
LSD($p = 0.05$)	PBR 0.085 IW: CPE 0.094 PBR × IW: CPE 0.211							
Pooled analysis (Year × PBR's × IW:CPE)								
LSD ($p = 0.05$)								
Year (Y) 0.083 PBR's 0.082 Y × PBR's 0.117 IW: CPE 0.081								
Y × IW: CPE 0.114 PBR's × IW: CPE 0.180 Y × PBR's × IW: CPE 0.225								

(SA, SB, TU, KNO_3 and no PBR denote salicylic acid, sodium benzoate, thiourea, potassium nitrate and control, respectively).

Table 4
Stalk yield as affected of by PBR's and applied water.

Treatment	Stalk yield (Mg ha^{-1})		
	2014–15	2015–16	Pooled
PBR's			
SA	8.89	7.75	8.32
SB	8.85	7.52	8.18
TU	8.53	7.36	7.95
KNO_3	8.05	7.02	7.53
No PBR	7.65	6.54	7.10
LSD ($p = 0.05$)	0.341	0.333	0.255
IW: CPE			
0.95	12.12	10.66	11.39
0.80	10.86	10.03	10.44
0.65	10.19	9.54	9.87
0.50	9.50	8.53	9.02
0.35	8.12	6.13	7.12
0.20	5.21	3.88	4.54
0.05	2.75	1.90	2.32
LSD ($p = 0.05$)			
IW: CPE	0.320	0.270	0.207
PBR × IW: CPE	0.716	0.604	0.462
Pooled analysis (Year × PBR's × IW: CPE)			
LSD ($p = 0.05$)			
Year (Y) 0.090 PBR's 0.173 Y × PBR's 0.244 IW: CPE 0.171			
Y × IW: CPE 0.242 PBR's × IW: CPE 0.382 Y × PBR's × IW: CPE 0.540			

(SA, SB, TU, KNO_3 and no PBR denote salicylic acid, sodium benzoate, thiourea, potassium nitrate and control, respectively).

lower than SB during 2014–15 but both were at par during 2015–16, which indicate towards the sensitivity of the response of PBR's to environmental conditions. Recently several other reports have also emerged on the beneficial role of PBR's in enhancing the growth and crop yields under stress environments e.g. in soybean (Hayat et al., 2010) and *Z. mays* (Saruhan et al., 2012) under drought with SA; in forage cowpea (Kumar et al., 2014) under high temperature stress and wheat (Beltrano et al., 1999) under water stress with SB, in *Brassica* with TU under salt stress (Pandey et al., 2013), in sorghum under drought (Dhanoji, 2010) and chickpea under salinity stress (Abdolahpour and Lotfi, 2014) with KNO_3.

The interactive effect of PBR's and supplemental irrigation was also significant during two years (Table 3). The average improvement in grain yield with PBR's ranged between 3.4–6.5,

Table 5
Growth and yield attributes as affected by PBR's and irrigation levels.

Treatment	Plant height (m)			Panicle size (Sphericity Index, Φ)			Grain weight (g)/panicle			1000 grain weight (g)			Harvest Index (HI)		
	2014–15	2015–16	Pooled	2014–15	2015–16	Pooled	2014–15	2015–16	Pooled	2014–15	2015–16	Pooled	2014–15	2015–16	Pooled
PBR's															
SA	2.55	2.22	2.39	37.3	31.4	34.4	48.8	39.5	44.2	34.9	29.1	32.0	0.245	0.221	0.233
SB	2.58	2.25	2.41	37.3	31.5	34.4	48.6	39.1	43.9	35.1	29.6	32.4	0.244	0.229	0.237
TU	2.45	2.18	2.32	36.0	30.5	33.2	45.7	37.2	41.5	33.9	28.4	31.2	0.239	0.227	0.233
KNO_3	2.32	2.06	2.19	34.5	28.9	31.7	42.6	34.4	38.5	32.2	26.9	29.6	0.231	0.214	0.223
no PBR	2.22	1.96	2.09	33.0	27.3	30.1	40.0	31.4	35.7	30.0	25.4	27.7	0.229	0.207	0.218
LSD (p=0.05)	0.074	0.088	0.043	1.02	0.84	0.82	2.21	1.93	1.50	1.35	1.21	1.17	0.007	0.010	0.007
IW: CPE															
0.95	3.25	2.99	3.12	38.1	35.6	36.9	60.3	55.3	57.8	38.8	36.0	37.4	0.233	0.250	0.242
0.80	3.04	2.95	2.99	39.1	36.0	37.5	62.2	55.9	59.1	37.9	36.1	37.0	0.259	0.262	0.261
0.65	3.00	2.70	2.85	39.1	32.9	36.0	63.3	50.4	56.9	37.0	32.5	34.8	0.276	0.253	0.265
0.50	2.81	2.44	2.62	36.8	29.2	33.0	56.2	42.0	49.1	32.8	28.7	30.8	0.265	0.231	0.248
0.35	2.33	1.89	2.11	34.5	26.3	30.4	39.5	29.0	34.3	30.1	24.4	27.3	0.227	0.212	0.220
0.20	1.66	1.22	1.44	32.0	25.1	28.5	22.8	15.2	19.0	28.5	20.8	24.7	0.209	0.185	0.197
0.05	0.87	0.76	0.81	29.7	24.4	27.1	11.7	6.4	9.1	27.4	16.7	22.1	0.194	0.143	0.169
LSD ($p = 0.05$)															
IW: CPE	0.047	0.049	0.035	0.53	0.65	0.38	1.56	1.43	1.21	1.00	0.64	0.65	0.007	0.009	0.006
PBR × IW:CPE	0.103	0.111	0.078	1.19	1.45	0.86	3.50	3.20	2.70	2.30	1.42	1.44	0.017	0.021	0.014

(SA, SB, TU, KNO_3 and no PBR denote salicylic acid, sodium benzoate, thiourea, potassium nitrate and control, respectively).

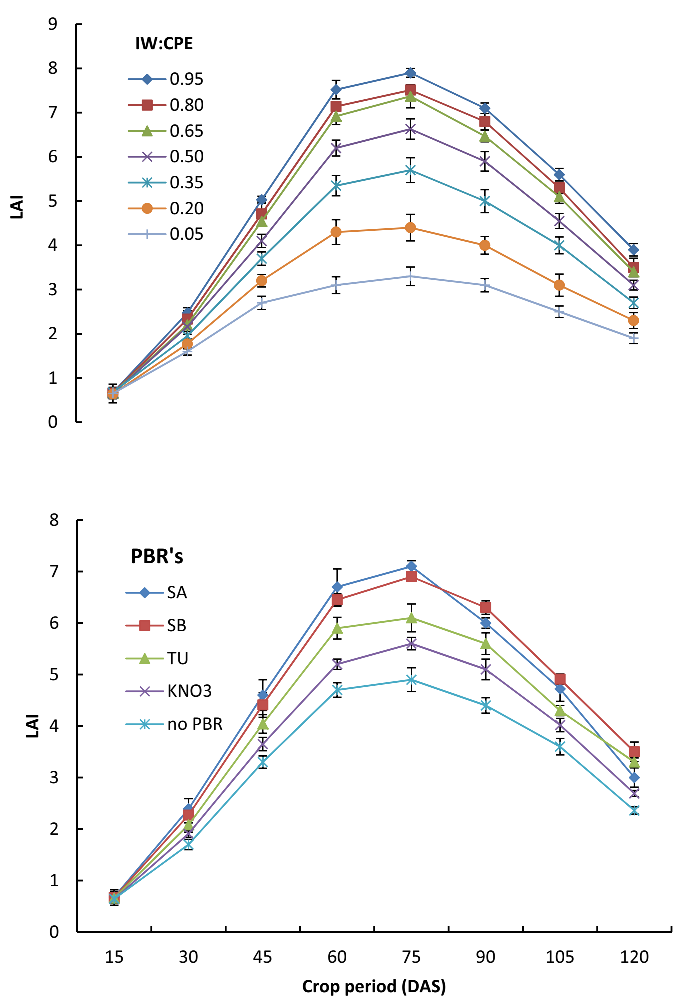

Fig. 2. Effect of PBR's and irrigation levels on LAI during different growth stages of sorghum.

9.9–17.9 and 26.2–57.4% under no (IW: CPE 0.95–0.80), moderate (0.79–0.50) and severe stress conditions (0.49–0.05), respectively indicating thereby better role of PBR's under the latter conditions. Especially SB and TU were quite effective under severe water deficit

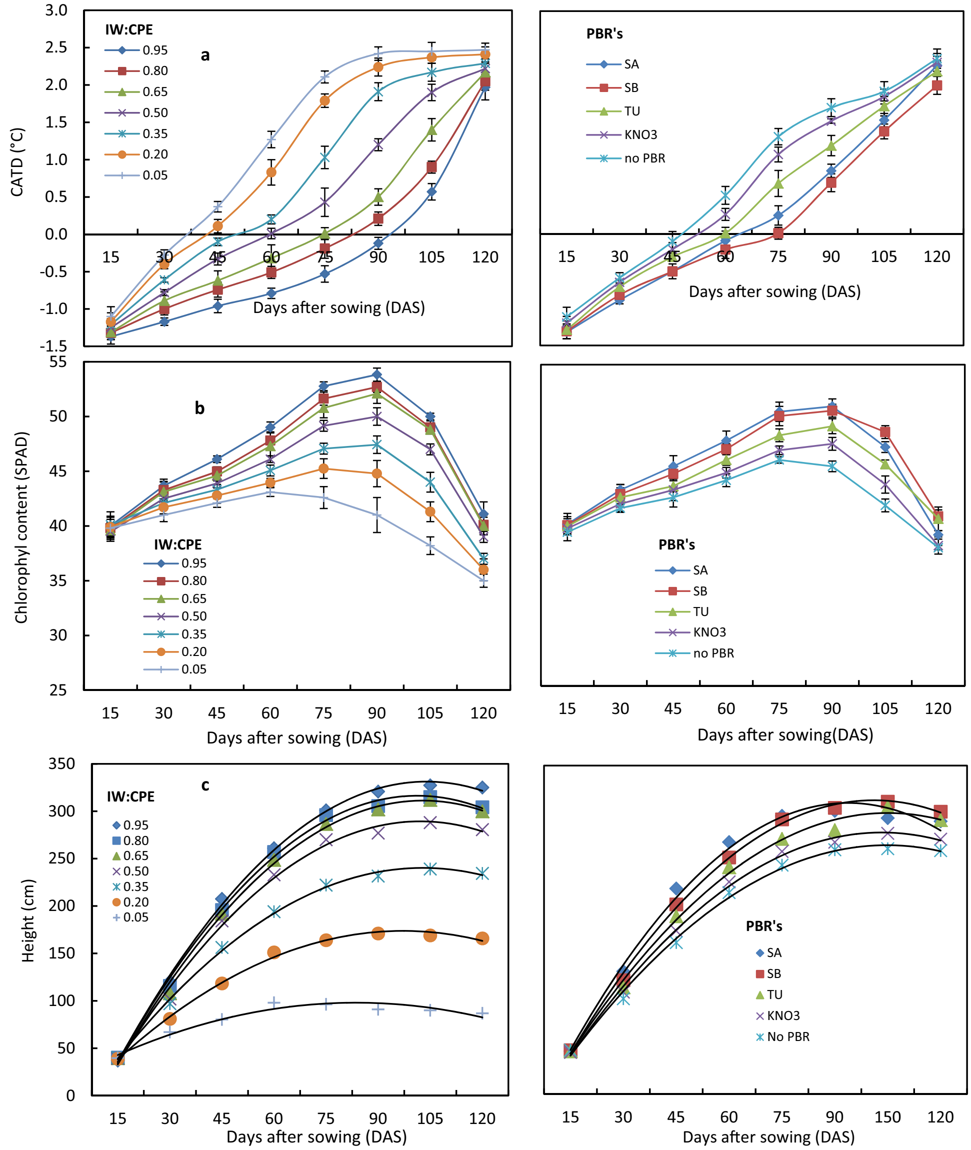

Fig. 3. Changes in (a) canopy air temperature difference (CATD), (b) chlorophyll content and (c) plant height of sorghum under different PBR's and irrigation levels at different days after sowing (DAS).

conditions e.g. RY at IW: CPE 0.20 were 84.0, 78.7, 70.7 and 26.7 with SB, SA, TU and KNO_3, respectively. Further, the improvement in yield with SB, SA and TU ranged between 23 and 37% at IW: CPE 0.35. The decline in RY with each IW: CPE of 0.1 equalled 0.43, 0.44, 0.47, 0.49 and 0.53 Mg ha^{-1} for SB, TU, KNO_3, SA and no PBR's, respectively that further indicates the better role of PBR's in alleviating water stress impacts. The stalk yield followed similar trend (Table 4) and the average improvement equalled 14.7, 13.2, 10.7 and 5.7% with application of SA, SB, TU, and KNO_3 over the control (no PBR), respectively.

3.2. Growth and yield attributes

Better growth and yield attributes were also monitored with PBR's (Table 5). The plant height and panicle size averaged between 2.19–2.41 m and 31.7–34.4 with application of PBR's while the respective values were lower i.e. 2.09 m and 30.1 without PBR's. Even the grain weight/panicle, 1000 grain weight and HI that averaged from 38.5–44.2 g, 29.6–32.4 g and 0.223–0.237 got improved with PBR's as against 35.7 g, 27.7 g and 0.218 for no PBR, respectively. The protective mechanism of PBR's regulates the root growth for improving plant water/nutrient status, photosynthetic efficiency and source–sink homeostasis resulting enhanced yield and metabolism for overall improvement in plant growth (Srivastava et al., 2016). Similar results with PBR's have earlier been reported by Dhanoji (2010).

The growth and yield attributes also responded to supplemental irrigation. The plant height got stunted with reduction in IW while SI was sustained (36.0–37.5) down to IW: CPE 0.65 and thereafter it ranged between 29.2–24.4. The average grain weight/panicle varied between 9.1–59.1 g and followed similar trend as of SI. The 1000 grain weight decreased from 37.4 to 22.1 g with reduction in quantity of IW. Similar variations in sorghum plant height (Hussein and Alva, 2014), panicle size (Craufurd and Peacock, 1993), seed weight/plant and 100 seed weight (Dhanoji, 2010) have been reported. HI ranged between 0.242–0.265 at IW: CPE 0.90–0.65 and got reduced to 0.248–0.169 with deficit irrigation. On the whole, the maximum values of growth and yield attributes were monitored at IW: CPE 0.95–0.80. Similar observations were reported by Farre and Faci (2006) for sorghum grown in Mediterranean environment.

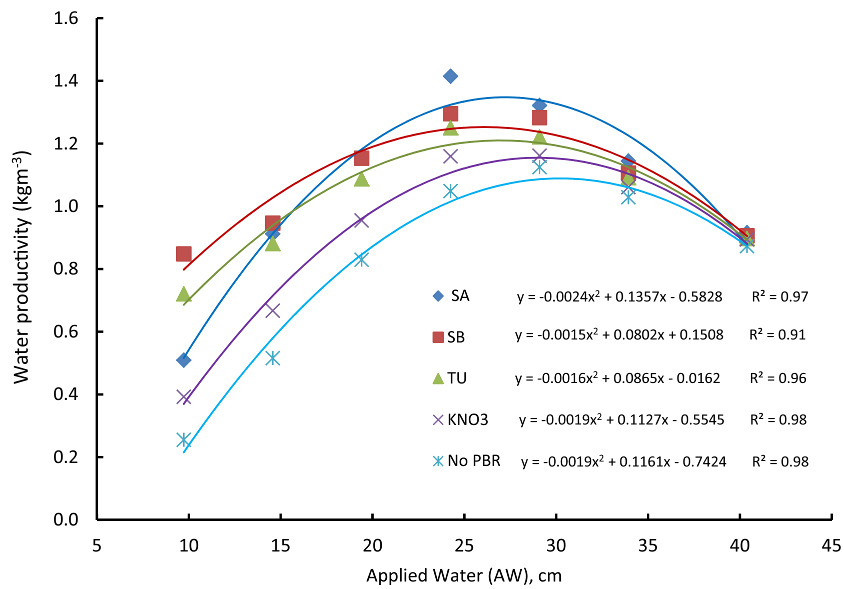

Fig. 4. Effect of PBR's on water productivity at various quantities of applied water (AW).

3.3. *Traits associated in alleviation of water stress*

The temporal changes in surrogated traits involved in alleviation of water stress *viz.*, LAI, CATD, chlorophyll content (SPAD) and plant height are depicted in Figs. 2 and 3. In general LAI, SPAD and plant height improved with increase in irrigation and their maximum values of 3.3–7.9, 41.0–53.8 and 0.90–3.27 m obtained at 75, 90 and 105 DAS, respectively. The maximum differences of 4.6 and 12.8 in LAI and SPAD were monitored between IW: CPE 0.95 and 0.05 at 75–90 DAS indicating that the crop was severely affected by water stress at lower irrigation levels. Similar reduction in LAI (Mastrorilli et al., 1999), chlorophyll content (Arivalagan and Somasundaram, 2015) and plant height (Hussein and Alva, 2014) was earlier reported under water stress conditions for sorghum. Obviously the chlorophyllase and peroxidase enzymes get increased with water stress and inhibit the chlorophyll content formulation that controls photosynthesis and plant growth (Arivalagan and Somasundaram, 2015).

LAI, SPAD and plant height that ranged between 0.64–7.10, 39.7–51.1 and 0.38–2.67 m with PBR's during different sorghum growth stages were higher than their respective values 0.65–4.9, 39.4–46.1, 0.40–2.24 m with no PBR. The PBR's helped to improve LAI (1.6–2.2) and SPAD (4.5–5.6) over control at most critical growth period (75–90 DAS) indicating the role of PBR's for enhancing photosynthesis and photosynthetically active leaf surface (Dhanoji, 2010; Arivalagan and Somasundaram, 2015). The CATD was monitored to be negative during 75–86 DAS at IW: CPE 0.65–0.95 indicating no stress at grain development stage, while positive values were monitored at 30–45 DAS with IW: CPE 0.05–0.50 indicating initiation of water stress from seed elongation stage. The maximum CATD difference 2.6 °C observed at panicle emergence followed by 2.5 °C in grain development and 2.1 °C in reproductive stages, respectively. This also indicates that sorghum is highly sensitive to water stress during these stages. The restricted water uptake for panicle emergence stage (75 DAS) at IW: CPE 0.50; reproductive stage (60 DAS) at IW: CPE 0.35; seedling elongation stage (20–45 DAS) at IW: CPE 0.20–0.05 and thus transpiration were reflected in terms of rise CATD. The canopy temperature has earlier been used as an indicator of crop water stress, since a reduction in plant available water results in lower transpiration rates and consequently higher canopy temperatures (Taghvaeian et al., 2014). Bandyopadhyay et al. (2014) reported that the rise in CATD values were mainly owing to lower relative water content and leaf water potential under deficit irrigation, factors accountable for water stress in wheat. The negative CATD (−0.36 to −0.0 °C) reported up to 52 DAS (reproductive stage) for all PBR's whereas no PBR's showed positive CATD (0.21 °C). Thereafter, CATD became positive at 53, 60, 64 and 75 DAS for KNO_3, TU, SA and SB, respectively representing relative response of PBR's to mitigate water stress. After panicle emergence stage (75 DAS), positive CATD sustained at low levels (0.01–1.07 °C) compared with without PBR (1.31 °C) indicating that the relatively better leaf water status was maintained until the grain development stage. Also as compared to control, PBR's reduced CATD ranged from 0.21–1.06 °C for different growth stages with maximum reduction in SB followed by SA at 75 DAS, indicating role of PBR's for maintenance of cooler canopy temperature under water stress conditions. Thus PBR's have greater role in maintaining canopy temperature and leaf water status for crop grown under heat and drought conditions (Srivastava et al., 2016). These results suggested that these surrogate traits greatly contributed in enhancement of grain yield with application of PBR's especially SB, SA and TU by maintaining leaf water status by closing stomata, increasing relative water content and cell turgor pressure under water deficit conditions.

3.4. *Water productivity (WP)as function of quantity of applied water (AW)*

WP, expressed as the ratio of sorghum grain yield to water consumption that includes irrigation water and rainfall was affected by both PBR's and the irrigation levels. In general for all PBR's, WP increased initially at no stress, remained stable at moderate stress and again decreased at severe stress conditions. The WP values ranged between 0.23–1.49 and 0.28–1.34 kg m^{-3} during the two years. WP ranged between 0.51–1.41, 0.85–1.30, 0.72–1.25, 0.39–1.16 and 0.26–1.12 kg m^{-3} with spray of SA, SB, TU and KNO_3 and no PBR, respectively. The improvement in WP with PBR's ranged between 3 and 7% at no stress; 10–18% at moderate stress; 23–55% at severe water stress conditions. Thus PBR's especially SA, SB and TU those had a major role in terms of maintenance of leaf water content, modulating the stomatal opening and water usage considerably enhanced WP under water stress conditions. Similar results were reported by Farre and Faci (2006) that WP in sorghum remained stable with moderate deficit irrigation and declined markedly with severe water deficit. However, Tolk and Howell (2008) have reported WP of sorghum to increase from 1.27 to 1.76 kg m^{-3} with water deficits for different soils. Nonetheless wide range of WP values has been reported for sorghum in different studies (Khan et al., 2013; Wakchaure et al., 2015).

Second degree polynomials best described (R^2 = 0.91–0.98) the relationship between AW and WP (Fig. 4). By using these relations, the maximum WP was computed to range from 1.12–1.34 kg m^{-3} with different PBR's whereas it was 1.03 kg m^{-3} with no PBR and the AW to attain the maximum WP was 26.7–29.7 cm with PBR's and 30.6 cm with no PBR indicating the role of PBR's in alleviating water stress. The AW to achieve WP equivalent to maximum with no PBR (1.03 kg m^{-3}) were computed to equal 15.4, 17.0, 18.3, 22.9 cm with SB, SA, TU and KNO_3, respectively indicating the possibilities of reducing irrigation water use by 25.2–49.7%. Further application of SA was more effective in improving WP at low stress levels while SB and TU performed better at higher stress. Overall improvements in WP were obviously exhibited through three plant processes *viz.,* improved root growth to support enhanced uptake of water and nutrient, increased photosynthetic efficiency and source to sink translocation to support crop yield and better metabolism to support overall growth of the plant (Srivastava et al., 2016). Farre and Faci (2006) reported similar curvilinear relationship while a negative linear model best defined the relationship between AW and WP for the sorghum (Tolk and Howell, 2008).

4. Conclusions

Amongst the PBR's tested, SB and TU were quite effective in improving the grain yield (6.8–18.5%) and water productivity (0.39–1.41 kg m^{-3}) of sorghum with an overall 25–49% reduction in irrigation water use to achieve similar water productivity as without PBR's. Thus these can help to mitigate water stress and promote the productivity vis–a–vis profitability of sorghum under water scarcity conditions. However for integrating the use of PBR's with supplemental irrigation, large scale testing is required for defining their economic spray schedules.

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