

YIELD AND WATER PRODUCTION FUNCTIONS OF WHEAT (*Triticum aestivum* L.) CULTIVARS AND RESPONSE TO EXOGENOUS APPLICATION OF THIOUREA AND ORTHO-SILICIC ACID

P. Ratnakumar*, P.S. Minhas, G.C. Wakchaure, R.L. Choudhary, P.P. Deokate

ICAR-National Institute of Abiotic Stress Management, Baramati- 413 115, Pune, Maharashtra

* Corresponding author.

ABSTRACT

Supplemental irrigation, drought tolerant cultivars and use of plant bioregulators are now being proposed as the key strategy to unlock the yield potential and stabilize the yield of wheat grown in rainfed areas. Experiments were therefore conducted during 2013-2015 using line source sprinklers (LSS) to determine the interactive effects of quantities of supplemental irrigation and exogenous foliar sprays of plant bioregulators- 10 mM thiourea (TU) and 32 ppm of ortho-silicic acid (OSA) on wheat (*Triticum aestivum* L.) varieties viz., HD2189, LOK1, NIAW 301, NIAW 34 and PBW 550. The irrigation quantities were: fully irrigated (I₁:31.8cm); mild (I₂: 28.9cm); medium (I₃: 25.9cm and I₄: 22.7cm); and severe (I₅: 19.9cm and I₆: 17.2cm) water stress conditions. Wheat cultivars varied in their response to water deficits and those popular with farmers e.g. NIAW-301 showed higher water productivity under deficit irrigation. Response to TU, OSA also varied across water regimes and was higher under moderate to severe stress. Foliar application of TU and OSA at root crown initiation, flag leaf and grain filling stages improved yield by 6-9 % at fully irrigated; 18-19% at medium stress; 12-17% at severe water stress conditions and water productivity by 0.12- 0.10 Mg h⁻¹ with TU, 0.13-0.09 Mg h⁻¹ with OSA at fully irrigated and medium stress; 0.11-0.03 Mg h⁻¹ with TU, 0.12-0.03 Mg h⁻¹ with OSA at severe stress conditions. TU and OSA induced efficient use of water through increased relative water content, modulating canopy temperatures and enhanced total soluble sugars and sink partition those are essential for enhanced water productivity under deficit irrigation. Our interpretation is that varieties like NIAW 301, NIAW 34 and LOK1 with higher water productivity under medium and severe water stress intensities, though having comparatively low potential yields, should be preferred and exogenous application of PBR's like TU and OSA could further enhance wheat productivity.

Keywords: Wheat cultivars; Deficit irrigation; Thiourea; Ortho-silicic acid; Water productivity

1. INTRODUCTION

Wheat productivity is primarily water-limited in arid and semi-arid regions especially where droughts are of frequent occurrence. Under limited irrigation water, reduction in grain yield mainly due to restricted in water availability that corresponding for seed filling and water stress intensity will depends on degree, duration and timing of deficit irrigation. Since irrigation is becoming both infrequent and expensive in recent times, several studies on plant responses to water deficits (stress) are being carried out by investigators concerned with agricultural production, environment and resources, and macroscopic physics of soil, plant, and atmospheric water. The line-source irrigation system has been used to determine the influence of several treatment variables and irrigation on yield and other traits (Singh et al 2009; Rao et al 2013). Therefore, these systems have been extensively deployed to evaluate wheat yield response to variable amounts of irrigation water (Jensen et al., 2001, Peel et al., 2004, Winward and Hill, 2007; Singh et al., 2009) and determining water requirements maize, wheat and herbaceous perennials (Kjelgren and Cerny, 2006).. However, several agronomic practices including the selection of appropriate cultivars make a difference under water stress conditions. Since the most prevalent varieties are not developed for water deficit conditions, their responses are highest under reliable irrigation supplies. Therefore, in addition to development of crop water production functions of wheat, the other objective was to identify appropriate varieties with better response to limited water in terms of water productivity.

In order to provide immediate solution to farmers under semi-arid regions of the concept of LEISA (Low External Input and Sustainable Agriculture) is gaining significant interest among scientific community. LEISA based agriculture system is based upon the options which are ecologically sound, economically feasible and culturally acceptable. This is generally achieved through the exogenous application of low concentration of chemicals termed as “Plant Bio-Regulators (PBRs)”. The plant stress tolerance can be improved with an exogenous use of stress alleviating chemicals (Wahid et al., 2007; Farooq et al., 2009). In the current scenario, various kinds of PBRs have been tested for enhancing the plant stress tolerance as well as the crop yield (Jisha et al., 2013). In LEISA, low level of PBRs are applied to the crop as foliar application to modulate the signaling associated with plant growth and yield; while, priming is mainly given during seed soaking stage to activate stress tolerance mechanism so that plants perform better upon subsequent stress exposure. Most of the PBRs treatments are applied either for seed priming or as foliar spray. Among the stress alleviating compounds, thiourea and ortho-silicic acid are the important molecules which have been shown to be beneficial for drought alleviation (Sahu et al 2006;Srivastava et al. 2009;Chen et al 2010; Meena et al 2013). The response to alleviation of water stress with application of PBRs may also vary among the cultivars. Therefore the present study was conducted with the objectives (i) to study the individual

response of wheat cultivars under various water regimes, (ii) to assess the cultivar response to bioregulators at each water stress intensity (iii) to answer what maximum amount of grain yield losses can be minimize using PBRs under stress conditions and (iv) to focus on the traits involved in advantage of grain yield under water stress condition using line source sprinkler system and exogenous application of TU and OSA. The research focused on effective use of water in wheat crop by exogenous application of bioregulators, and cultivar responses at different intensity of water stress and to address the mitigation strategies of wheat cultivated in water scarcity zones of semi-arid regions.

2. MATERIALS AND METHODS

2.1 Experimental Details

Field experiments were conducted at NIASM experimental farm, Baramati, located in Southern-Western State of India (18°9' TNT, 74°28' E) during two growing seasons, 2013- 2014, and 2014-2015, in a black 60-70 cm deep silty clay (around 40 % clay) over native basaltic soil. A line source sprinkler system with eight sprinklers spaced at 6.1 m was designed to provide for usable experimental area of size 24.4 m x 24.4 m. The system delivered linearly decreasing water distribution pattern at 24.4 m wetted diameter under 300 kPa pressure (figure 1). The detailed specification of sprinkler system is; HDPE pipe (75 mm dia. and 6.1m length), metal split nozzles with spreader (5.1 mm x 3.1 mm), riser (GI pipe, 12.5 mm dia. and 1.84 m height), HDPE service saddle (75 mm dia.) and HDPE pump connector (with gasket, end cap and tee bend, 75 mm dia.). The symmetrical water distribution pattern was monitored by using a series of PVC catch cans placed perpendicular to the line source system at 2 m spacing. The decrease in water distribution was observed with increase in distance from main line of LSS. The maximum water delivered was 19 mm/h near the main line and the lowest was 0.4-0.7 mm at a radius of 12.2 m. The field experiments were conducted in split plot design with four replications. Fifteen main plot treatments consisted of combinations of five varieties of wheat, namely NIAW 34 (Pedigree: CIANO-79/(SIB) Parula; year of released: 1997) , NIAW 301(Pedigree: Seri-82/Hork; year of released: 2002), HD-2189 (Pedigree: HD 1963/ HD 1931; year of released: 1980), LOK-1(Pedigree: S-308 X S-331 (Sonalika x Chhoti larma); year of released: 1979), PBW 550 (Pedigree: WH 594/RAJ 3858//W 485; year of released: 2007) and two bioregulators viz. thiourea and ortho-silicic acid. Each main plot was sub-divided into six subplots 2m horizontally based on irrigation received from line source sprinkler system. Six levels of irrigation based upon the climatological approach i.e. ratio of cumulative USWB class A open pan evaporation (CPE) and depth of irrigation water (IW). The maximum IW at each irrigation varied between 6.5 to 7.4 cm that was equivalent to CPE (IW:CPE 1.0) and happened to be in the nearest subplot to main sprinkler line. The irrigation quantities were: fully irrigated (I₁:31.8cm); mild (I₂: 28.9cm);

medium (I₃: 25.9cm and I₄: 22.7cm); and severe (I₅: 19.9cm and I₆: 17.2cm) water stress conditions. The crop was planted in early November, with a seed sowing rate of 100 kg ha⁻¹ using seed drill. Mean temperature during grain filling was around 25.5°C in the two year, with averaged maximum temperatures of 29°C. Seasonal precipitations ranged from 8- 76mm. Plots were fertilized with 120 kg N, 60 Kg P₂O₅ and 40 Kg K₂O ha⁻¹. Half of N was applied as basal dose while rest was applied in two equal splits i.e. at CRI and tillering stage. Different concentrations viz., 32 ppm stabilized silicic acid (*Brand: silixol; Make: Privi*) and thiourea 10 mM were applied as foliar sprays at crown root initiation at 15 days after sowing (DAS), flag leaf, flowering and maturation stage and where water was sprayed in control plots. Protection measurements were taken while application of foliar sprays.

Figure1: Experimental design. Irrigation water applied (cm) as a function of distance from line source sprinkler. The symmetrical water distribution pattern was monitored by using a series of PVC catch cans placed perpendicular to the line source system at 2 m spacing. The decrease in water distribution was observed with increase in distance from main line of LSS. The maximum water delivered was 19 mm h⁻¹ near the main line and the lowest was 0.4-0.7 mm at a radius of 12.2 m. The experiments were conducted in split plot design with four replications. Fifteen main plot treatments consisted of combinations of five varieties of wheat with TU, OSA and water as control (c) from 1 to 15 combinations are given bellow.

1	HD 2189 +TU	6	HD 2189 +OSA	11	HD 2189 +C
2	LOK 1 +TU	7	LOK 1 +OSA	12	LOK 1 +C
3	NIAW 301 +TU	8	NIAW 301 +OSA	13	NIAW 301 +C
4	NIAW 34 + TU	9	NIAW 34 + OSA	14	NIAW 34 + C
5	PBW + TU	10	PBW + OSA	15	PBW + C

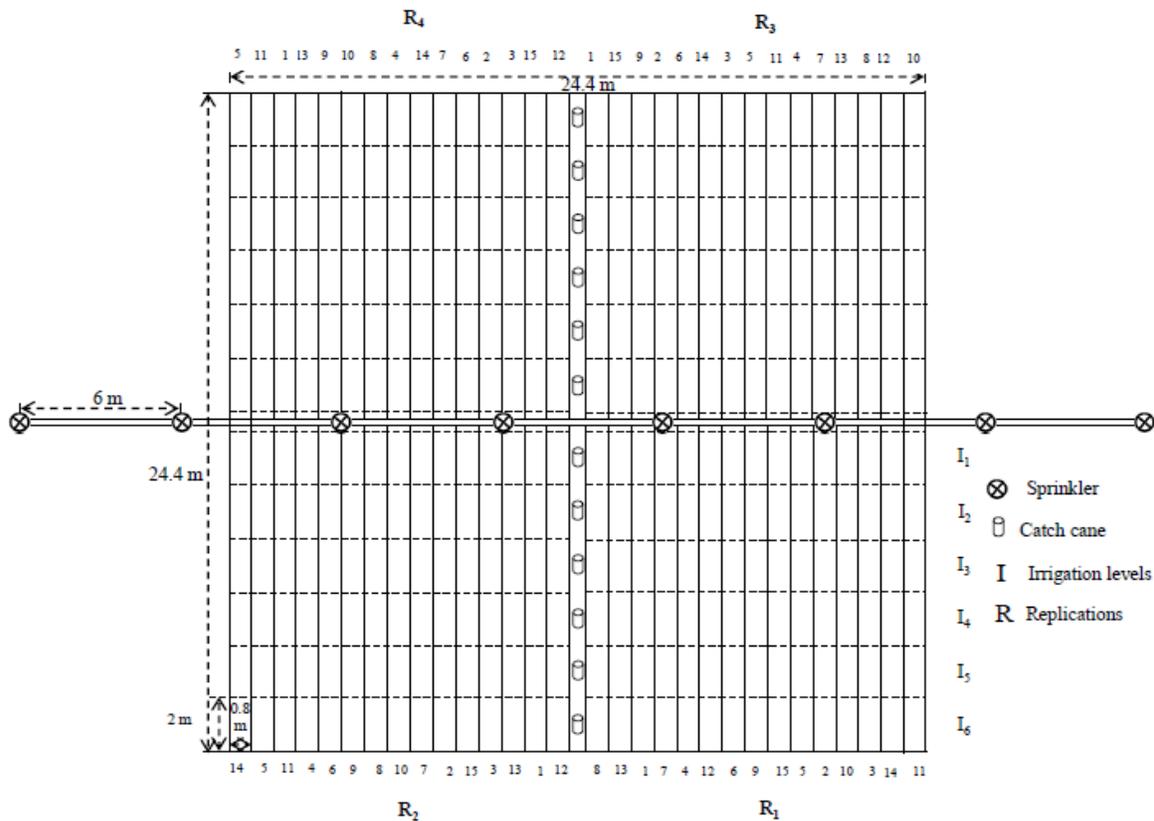


Figure 1.

2.2 Growth, Yield and Agro-Physiological parameters Monitoring

The plants were harvested after physiological maturity, and separated into leaf and tillers fractions. Plant height, peduncle length and spike length of each plant were measured in each subplot of water treatments with bioregulators and control (water sprayed) plots. Dry weights of plant parts and seeds were measured after drying at 80°C in a hot air oven for 48 to 72 hours. The surrogate traits such SPAD, total soluble carbohydrates were also assessed to understand the carbon fixation to water deficit.

Canopy temperature was recorded by thermal imager (Vario Cam®hr inspect 575, Jenoptic, Germany) that operates in the wavebands 8-14 μm with a thermal resolution of 0.01°C. Thermal images with spatial resolution of 768 x 576 pixels were captured seven times covering crop growth stages just before and after anthesis. All thermal images were taken with the thermal imager on a tripod perpendicular to the area being imaged. Dry and wet references were used to mimic leaves with fully closed and fully open stomata, respectively (Jones et al., 2002) and to avoid extreme conditions while capturing images. Emissivity for all the measurements were set

at 0.96 (Jones, 2004). IRBIS® software (Jenoptic, Germany) was used to analyse images. A total of six areas of interest in each image for analysis in the imager's software were outlined manually, by comparing thermal and normal digital images to exclude noise from ground area. Minimum canopy temperature in each of the sections in each image was considered to get a value that represent cooling capacity of cultivar.

Relative water content (RWC) was measured as reported in Kumar & Elston, (1992). Known amount (w) of fresh leaf tissue collected from five plants of each treatment was incubated for four hours in distilled water. After 4 hours the samples are taken out of water and are well dried of any surface moisture quickly and lightly with filter paper and immediately weighed to obtain fully turgid weight (TW). Samples are then oven dried at 80°C for 24h and weighed (after being cooled down in a desiccator) to determine dry weight (DW). All weighing were done to the nearest mg. RWC was calculated as: $RWC (\%) = [(W-DW) / (TW-DW)] \times 100$. Here, W – sample fresh weight; TW – sample turgid weight; DW – sample dry weight. Chlorophyll content using SPAD chlorophyll meter (SPAD-502Plus, *Konica Minolta make*) in flag leaf of each cultivar from each treatment.

Total soluble saccharides were measured at grain filling stage from randomly collected leaf tissue. Fresh leaf samples were collected from field conditions at 4°C chill boxes. 100 mg of leaf tissue was extracted in 80% ethanol; soluble saccharides were measured using anthron reagent (DuBois et al., 1956) using UV- Vis spectrophotometer. Soil moisture was measured weekly interval at two depths at 15 and 30 cm by gravimetric method. Soil samples were oven dried at 105 °C and moisture content (%) was determined.

2.3 Statistical analysis

The results analysed using GENSTAT program version 10 (Genstat, Release 10.1). The general analysis of variance were performed to assess the effects of water treatment (T) and cultivar-by-water treatment (G * T) interaction plant bioregulators and cultivar-by-plant bioregulators treatment (G * PBR) interaction, interaction within season (G * T * PBR), for the different traits measured. The significance of genetic variability across treatments was also assessed. The purpose of these different analyses was to assess different possibilities of either interactions between cultivars, treatments and the season. Graphs were plotted using line and scatter plot of linear regression, Sigma Plot 10.

3. RESULTS

3.1 Interactive effect of PBRs and water treatments on yield

In both season experiments, the three way ANOVA showed highly significant genotypic variations on the total biomass, relative water content, SPAD chlorophyll readings, total sugars, canopy temperature and seed yield (Table 1), and also significant cultivar-by-water treatment-by-PBR treatment (G x Water Trt x PBR Trt) interaction for these traits. However, the magnitude of the genotypic variations was higher than the G x Water Trt x PBR Trt interactions in the haulm yield and haulm N. There was highly significant genotypic effect in all these traits but not in the G x Water Trt x PBR Trt interaction (Table 1.) The grain yield was drastically decreased with increased intensity of water stress in both seasons. The window of time period from flowering to maturity was also varied among the cultivars and with water levels applied. The variety NIAW 301 seeds matured in shorter window, though it was 10 days delayed flowered as compared with other varieties. The total grain yield of cultivars was varied among the varieties by the applications of TU and OSA under various water regimes. The average grain yields were increased with TU from 9 to 19 % OSA from 6 to 18 %. Under irrigated conditions TU and OSA enhanced 9, 6 %; under medium stress conditions 19, 18 %; and under severe water stress conditions 17, 12% with respective their control. These results indicate that the cultivars responded better with TU and OSA under moderate and severe stress than fully irrigated conditions. The maximum grain yield was found in NIAW 301 with TU under all irrigation conditions and the percent increase was higher among the varieties. The maximum percent of grain yield increased with application of TU and OSA in cultivars NIAW 301 followed by PBW 550, NIAW 34, HD 2189 And LOK 1 under various amount water applied (Figure 2). However, the yield response varied among the cultivars was observed under various water stress conditions, after dividing them in to three windows based on the amount of water applied, *i. e.* full irrigation applied (26 to 32 cm), medium water stress (22 to 26 cm), and severe water stress (17 to 22 cm) conditions. The foliar application of OSA has enhanced the grain yield in cultivars LOK 1, PBW 550 under maximum water applied, HD 2189, NIAW 301 under medium water stress, while the cultivar NIAW 301, NIAW 34 under severe water stress conditions. Whereas with the application of TU the cultivar NIAW 301, NIAW 34, PBW 550 showed maximum grain yield under maximum water applied, NIAW 301, NIAW 34, HD2189 under medium stress, NIAW 301, LOK 1, HD2189 and NIAW 34 under severe stress conditions as compared with their respective controls.

Supplement table 1. Three-way ANOVA on total biomass, RWC, SPAD, total sugars, canopy temperature and seed yield parameters of wheat varieties, water treatments and bioregulators and their interactions.

		Total biomass	RWC	SPAD	Total sugars	Canopy temperature	Seed Yield
Varieties (G)	Sum of square	351.325	655.223	1005.648	829.215	142.823	90.033
	Mean sum of square	70.265	131.045	201.130	165.843	28.565	18.007
	Variance (F Value)	26.407	1.720	1.442	6.970	9.715	15.215
	F. Prob.	0.001	0.144	0.222	0.001	0.001	0.001
	LSD	0.356	1.905	2.577	1.064	0.374	0.237
Water treatments (Water trt)	Sum of square	669.642	2340.833	974.008	281.228	472.472	81.608
	Mean sum of square	111.607	390.139	162.335	46.871	78.745	13.601
	Variance (F Value)	41.945	5.120	1.164	1.970	26.781	11.493
	F. Prob.	0.001	0.001	0.338	0.084	0.001	0.001
	LSD	0.384	2.057	2.783	1.150	0.404	0.256
Bioregulators (PBR)	Sum of square	38.730	127.233	429.249	271.022	25.272	1.210
	Mean sum of square	16.365	63.616	214.624	135.511	12.636	0.605
	Variance (F Value)	7.278	0.835	1.539	5.695	4.297	0.511
	F. Prob.	0.001	0.439	0.223	0.005	0.018	0.602
	LSD	0.252	1.347	1.822	0.753	0.265	0.168
G x Water trt	Sum of square	6868365	934.22	1007.98	546591	1612814	2827534
	Mean sum of square	490598	66.73	72	39042	115201	201967
	Variance (F Value)	5.57	3.34	5.36	3.42	5.36	6.44
	F. Prob.	0.001	0.001	0.001	0.001	0.001	0.001
	LSD	293	4.412	3.619	105.46	144.77	174.8
G x PBR	Sum of square	4402842	818.18	585.84	546591	937418	1870397
	Mean sum of square	314489	58.44	41.85	39042	66958	133600
	Variance (F Value)	3.57	2.92	3.11	3.42	3.11	4.26
	F. Prob.	0.001	0.001	0.001	0.001	0.001	0.001
	LSD	293	4.412	3.619	105.46	144.77	174.8
G x PBR x Water trt	Sum of square	2863099	488.48	758.59	314860	1213714	1358752
	Mean sum of square	204507	34.89	54.19	22490	86694	97054
	Variance (F Value)	2.32	1.75	4.03	1.97	4.03	3.1
	F. Prob.	0.006	0.051	0.001	0.023	0.001	0.001
	LSD	414.4	6.24	5.118	149.14	204.73	247.2

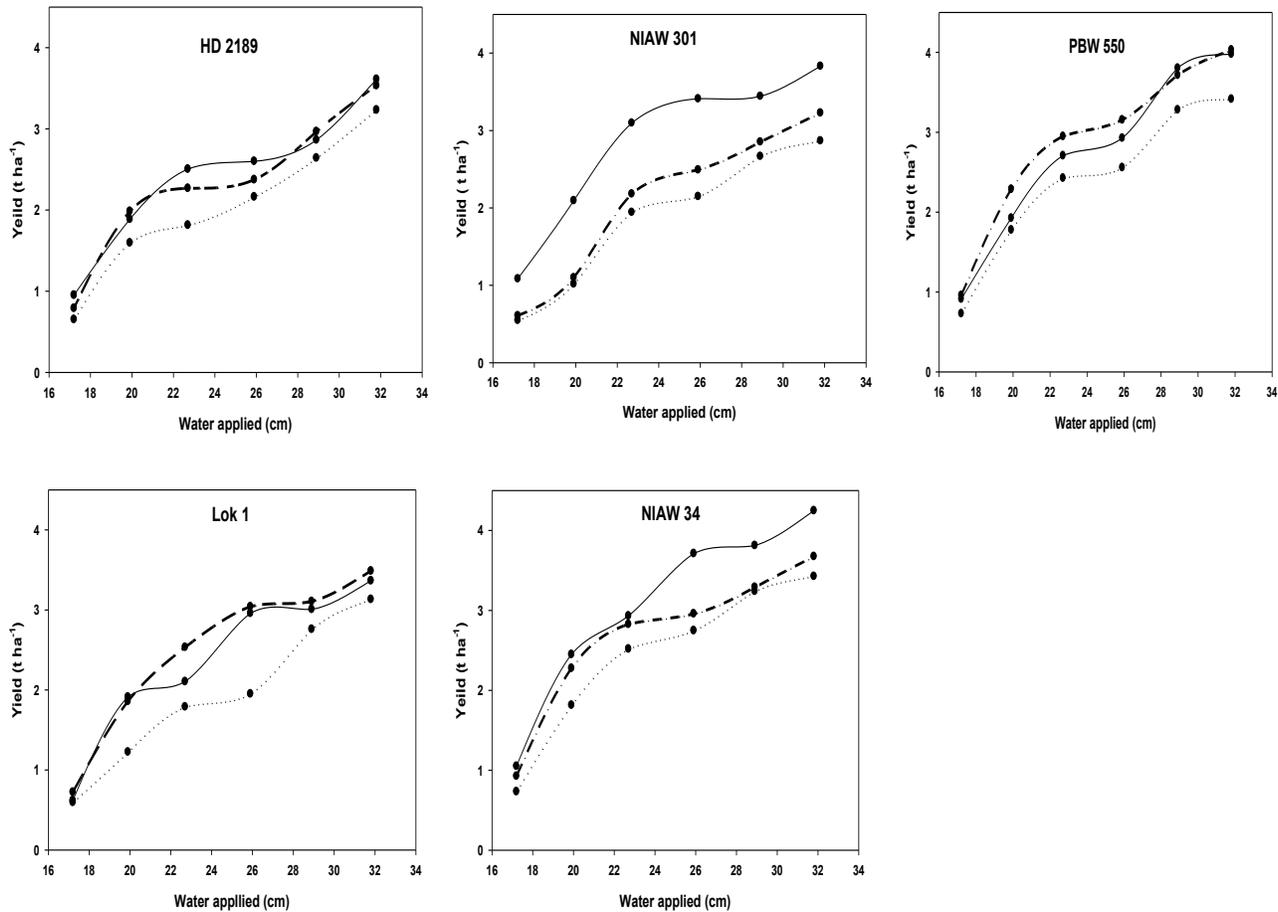
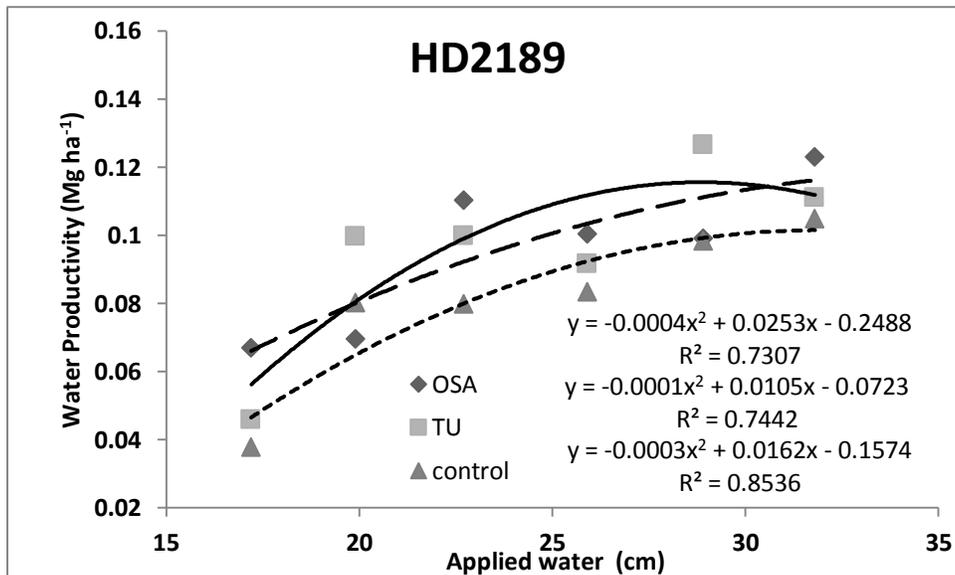


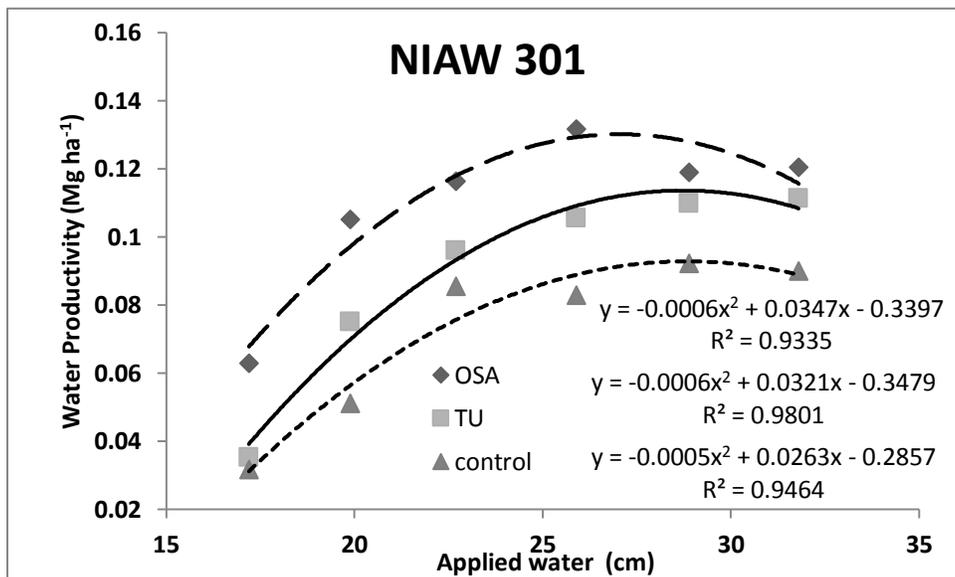
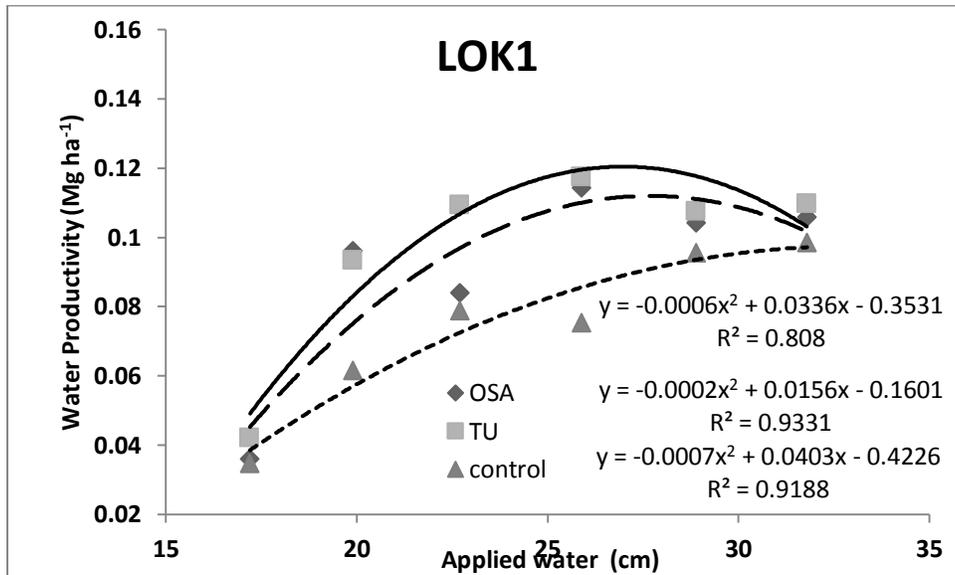
Figure 2: Yield (t ha⁻¹) responses of wheat varieties (HD 2189, NIAW 34, PBW550, LOK 1 and NIAW 34) to TU (thick continuous line), OSA (thick dotted line) and water (small dotted line) foliar application under various water stress conditions where total water applied (cm) from 17 to 32cm using line source sprinkler system. Graphs were plotted using line and scatter plot of linear regression, Sigma Plot 10. Data presented was the pooled seed yield data of two years.

3.2 Water productivity as a function of water quantity

Irrigation in both seasons increased water productivity, the relationship between water productivity and quantity water applied in cm was increased with TU and OSA application showed as compared with control (Figure 4). Wheat varieties were responded differently with TU and OSA application across deficit irrigation applied whereas increased in water productivity 0.12- 0.10 Mg h⁻¹ with TU, 0.13-0.09 Mg h⁻¹ with OSA at fully irrigated and medium water stress while 0.11-0.03 Mg h⁻¹ with TU, 0.12-0.03 Mg h⁻¹ with OSA at severe stress conditions.

The productivity of total applied water (PAW) is defined as crop yield per unit volume of water supply to the crop. The PAW was recorded in varieties PBW 550 and NAIW 34 (0.13 Mg h⁻¹ with OSA; 0.12 Mg h⁻¹ with TU) at irrigated conditions; in NIAW 301 and PBW 550 (0.13 Mg h⁻¹ with OSA; 0.12 Mg h⁻¹ with TU) at medium; and in NIAW 34, PBW 550 and NIAW 34 (0.12 Mg h⁻¹ with OSA; 0.11 Mg h⁻¹ with TU) compare to other two varieties. The average percent of water productivity increased among the cultivars from 15 to 32 % with TU and 16 to 35% with OSA compared with control. Maximum percent increase in PAW found in NIAW 301 with OSA and LOK1 with TU and minimum in NIAW 34 with TU and LOK1 with OSA; and moderate enhanced in HD2189 and PBW 550 respectively.





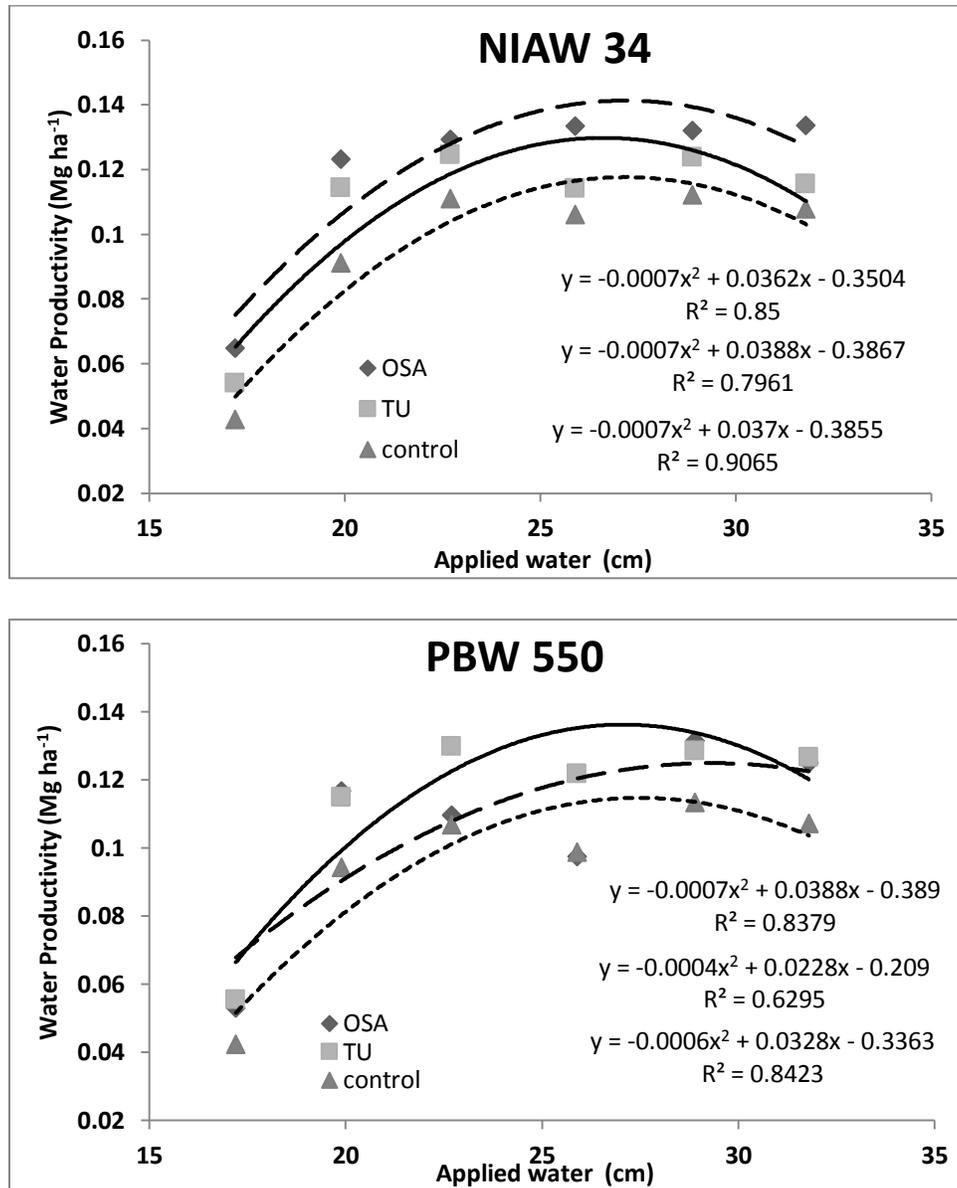


Figure 4: Water productivity (Mg ha⁻¹) of wheat varieties in response to foliar application of TU (strait line), OSA (broad dotted line) and water as control (dotted line) under various amount of irrigated water applied (cm). Trend of differential response of each variety expressed to TU and OSA in comparison with water expressed using simple polynomial curve. Data presented was mean data of six samples with four replications.

3.3 Relationship between canopy temperatures and yield

The canopy temperatures at seed filling stage were decreased with increased amount of water applied through irrigation and the relationship between canopy temperatures and yield was negative in all genotypes with foliar application of TU and OSA (Figure 3). The minimum canopy temperatures were found in NIAW 301 (22 to 26 °C) with TU and OSA than control. The yield was decreased with increased canopy temperatures with water stress intense conditions in all cultivars. The average higher canopy temperatures were at severe water stress conditions and minimum were at well irrigated conditions. The minimum temperatures did not vary much among the cultivars. The foliar application of TU and OSA increased canopy temperatures in varieties HD 2189, LOK 1, NIAW 34, PBW 550, but not much in NIAW 301. These results indicate that due to application of TU and OSA under deficit irrigated conditions in helped in stomatal closure to save water loss in all varieties except NIAW 301 which decreased the canopy temperatures than that of control enhances the water use that corresponding to grain filling by cooling canopy temperatures. The differential response of varieties in water saving and efficient water use enhanced grain yield under water stress and irrigated conditions. Variety NIAW 301 has cooler canopy and efficient use of water for its seed filling.

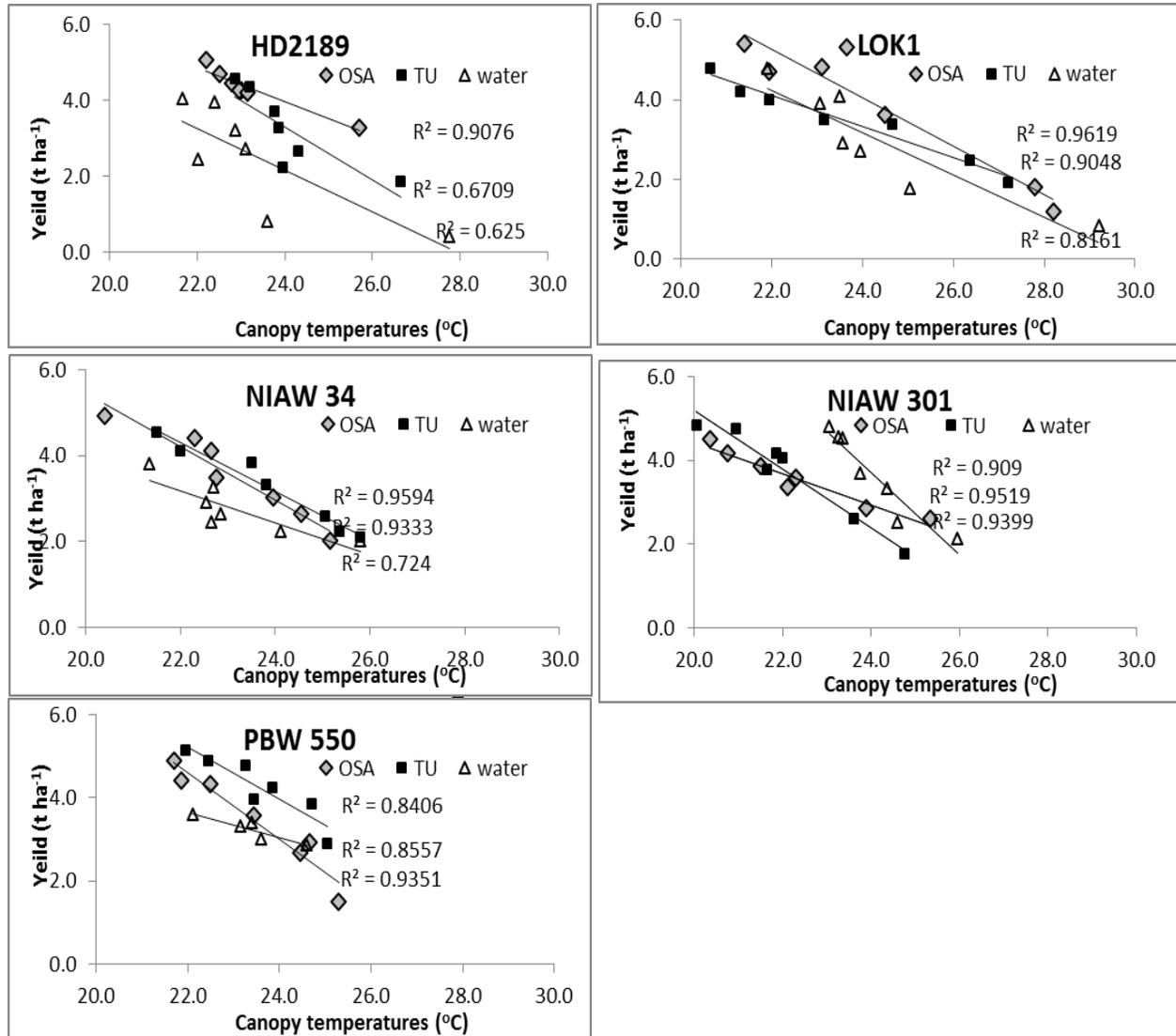
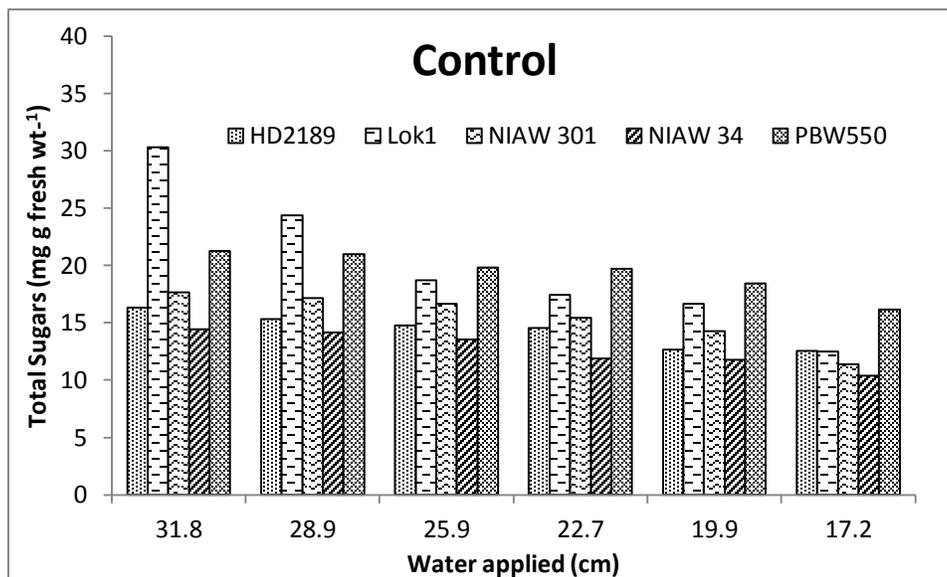


Figure 3: The relationship between yield (t ha⁻¹) and canopy temperature (°C) in wheat varieties with foliar application of TU, OSA and water as control under different water regimes. Each point expresses the yield and canopy temperature of each water applied (cm) with line source sprinkler system. Data presented was the pooled seed yield data of two years.

The photosynthates accumulated in the form of total saccharides that were estimated in flag leaf at seed filling stage were considered as a major source at the time of grain filling. The total soluble sugars varied significantly among the cultivars, under water treatments, with the exogenous application of TU and OSA and their interaction (Table -1). The varieties differed in the accumulation of total soluble sugars along under water treatments. With the foliar application of TU the maximum total soluble sugars were found in LOK1 followed by NIAW 301, HD 2189, PBW 550 and NIAW 34 (Figure 5). Similar trend followed by cultivars found with application of OSA, but the amount of total sugars (mg g⁻¹ fresh weight) was less compared to TU and more than the control. However, the sink in terms of grain yield was maximum in NIAW 301, followed by NIAW 34, PBW 550 and LOK1 (Figure 1) with application of TU. The OSA had enhanced the grain yield in LOK1 and PBW 550 under medium stress. Under normal conditions LOK1 has more source of accumulation and less grain yield potential, but it got enhanced sink with application of OSA and TU. These results indicate that each cultivar performed differentially in source accumulation and sink preservation with application of TU and OSA under various water regimes.



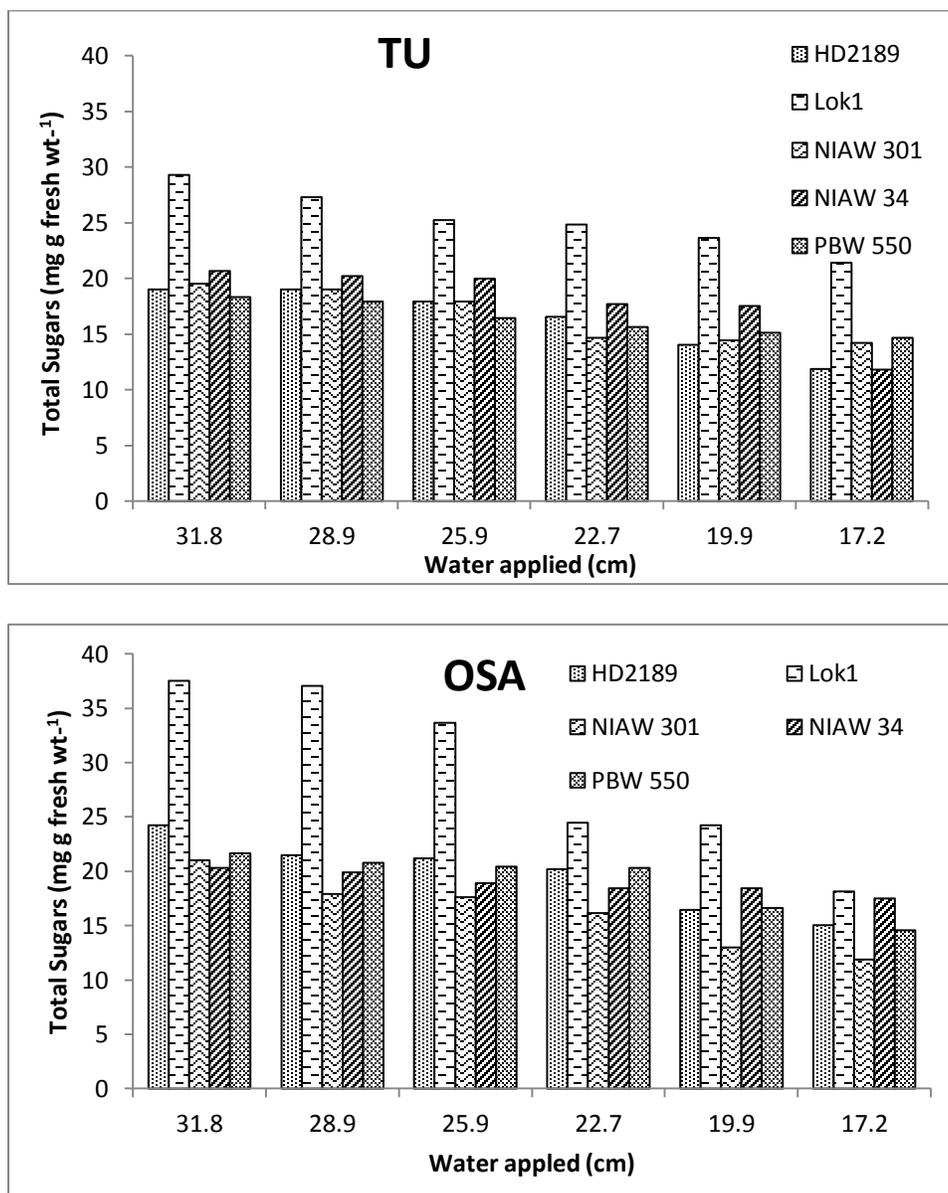


Figure 5: Differential responses wheat varieties for total soluble sugars (TSS) (mg g⁻¹ fresh wt.) with foliar application of TU, OSA and water as control under various water regimes. All cultivars showed same trend of decreased in TSS with reduced water applied (cm); TU and OSA enhanced the accumulation of TSS under water stress conditions as compared with its respective control. Data presented was mean data of six samples with four replications.

3.5 Traits associated in alleviation of water stress

In many studies SPAD chlorophyll and RWC were considered as surrogate traits for water stress tolerance. In present study focused on SPAD chlorophyll and RWC estimation to identify the possible surrogate traits that were involved in alleviation of water stress with the exogenous application of TU and OSA. The traits RWC, SPAD chlorophyll meter readings measured in flag leaf after application of TU and OSA under different water regimes were significantly varied among cultivars, with TU and OSA application and across all water regimes and their interactions (Table 1). RWC was higher under medium and severe stress conditions compare to control and it got enhanced with application of TU and OSA. SPAD chlorophyll readings were enhanced with application of TU and OSA under mild and severe water stress conditions and these results were not much significant among cultivars due to the cultivars selected for this study were differ in their leaf size and thickness.

4. DISCUSSION

4.1 Interactive effect of PBRs and water treatments on yield

The variation among the cultivars for grain yield enhanced with exogenous application of TU and OSA under all irrigated conditions, and especially under moderate and severe water stress conditions. This indicates that TU and OSA have differential role in alleviating water stress that was imposed using line source sprinkler system. These results agree with previous findings where TU was used to alleviate the abiotic stress especially for drought in *maize* as foliar application (Amin et al., 2013), in wheat as soil application (Sahu et al., 1995), in green gram under arid regions (Mathur et al., 2006) and for salinity in *brassica* (Srivastava et al., 2009) and in potato under normal condition (Mani et al., 2013). Silicon in various forms through soil application to alleviate salt stress in sorghum (Yin et al., 2013), in rice (Gurmini et al., 2013; Farroq et al 2015), cadmium stress alleviation in *durum wheat* (Rizwan et al., 2012), potassium deficiency in soybean (Miao et al., 2010). The intensity of stress affected the reproductive process as it showed drop in grain yield under moderate and severe water stress conditions in all cultivars under control (figure 2) and with application of TU and OSA got enhanced up to 18 % under severe water stress conditions. The cultivars NIAW 301, NIAW 34, PBW 550 and HD2189 that performed better with TU and LOK1, PBW 550 and HD2189 performed better with OSA application under severe stress conditions those that have success in their reproductive process.

4.2 Water productivity as a function of water quantity

The results of measured water productivity indicate that application of TU sulfhydryl compound and OSA beneficial element not only increased the grain yield but also increased the water productivity in study both years. Rahman et al. (1999) also reported a linear relationship between water use, yield, and yield components of wheat under various irrigation and nitrogen application treatments. With crop–water production functions and knowledge of the stages of the crop that are sensitive to water stress, optimal deficit irrigation and application of PBRs can be scheduled with a minimum yield reduction compared with full irrigation and, therefore, limited water resources can be utilized more efficiently. In addition, when the crop production functions are known, it is possible to appropriately allocate limited water resources between crops where crops compete for scarce water in dry areas.

4.3 Relationship between canopy temperatures and yield

The minimum temperatures were found in all cultivars under irrigated conditions than water stress conditions and these were reduced with application of TU and OSA (Figure 3). The negative relationship between canopy temperatures and yield shows that increase in canopy temperatures due to stomatal closure for water saving was reduced grain yields under water stress conditions. Under severe stress conditions with application of TU and OSA canopy temperatures got reduced compare to its control, and that ultimately enhanced grain yield was observed. Capacities of cooler canopy have been often associated with the water corresponded to grain yield in wheat (Mason and Singh, 2014) similar results were observed in NAIW 301 under all irrigated conditions with TU and OSA that enhanced water use and yield. Looking at the structure of thiourea, both ‘imino’ and ‘thiol’ functional groups has great implications in water stress tolerance. With foliar spray imino group provides a ready source of nitrogen and thiol has a great role in alleviating oxidative stress damage on the physiologically more important mesophyll tissue (Wahid et al., 2007). Under water stress conditions exogenous application of Si reduces water loss, while an epidermal cell wall with less silica will allow water to escape at an accelerated rate (Meena et al., 2013). These results clearly show that TU and OSA have much influence on epidermal and mesophyll cells to modulate the stomatal movement under stress conditions by reducing water loss in all varieties except NAIW 301.

4.4 Source and sink relation among varieties

The cultivars NIAW 301, PBW 550 and HD2189 exhibited enhanced grain yield with TU and OSA (Figure 1) and with enhanced total soluble sugars (Figure 5) under medium and severe stress conditions, probably these cultivars utilized carbohydrates (reserve) for grain development and source may not be the limiting factor. These results were also strengthened by previous finding that TU involved in the phloem transport of sucrose and in the substrate binding site of

the amino acid carrier (McCormick and Johnstone, 1990) and TU enhances the formation of the ternary complex, sucrose H⁺ carrier, thus improving translocation of photosynthates during grain filling in cereals (Hernández et al., 1983). Metabolic transport of sucrose to grains via effects on phloem loading enhanced with application of TU. Mobilization of dry matter (reserves) from leaves to grains increased in wheat with TU spray at tiller stage. Improvement in harvest index under TU treatments lends further credence to the role of TU in improving dry matter partitioning to grains (Sahu and Solanki, 1991). Likewise under water stress, Kaya et al. (2006) reported that Si significantly increased the dry weight of shoots and total biomass of maize.

4.5 Traits associated in alleviation of water stress

Increased relative water content, indicating retention of water in cells that leads to enhanced water stress tolerance and reduced proline level was observed when Si was applied to wheat grown under salinity (Tuna et al., 2008). In present study, OSA increased resistance of plant to water stress and improved water status. Similar studies were reported in sorghum (Hattori et al., 2005), maize (Kaya et al., 2006) and wheat with soil silica application (Pei et al., 2010). The foliar application of 32 ppm of OSA under water stress was highly subjective in holding maximum relative water content (RWC), maintenance of cooler canopy and increased chlorophyll content along with root profile in wheat crop to sustain under water stress conditions (Ratnakumar et al., 2015). A recent study also showed that silicon induced alleviation was independent of leaf water status (Hattori et al., 2008). TU and OSA significantly increased SPAD chlorophyll in all cultivars that were tested, similarly in maize, foliar spray of TU increased both canopy photosynthesis and photosynthetically active leaf surface during grain filling (Sahu et al., 1993) and OSA largely improved the total DM, chlorophyll content, RWC and proline accumulation (Meena et al., 2013). These results suggested that the surrogate traits RWC and SPAD chlorophyll content have contribution in grain yield under water stress which was greatly enhanced by TU and OSA.

5. CONCLUSION

In conclusion, variations among the wheat cultivars were confirmed in response to TU, OSA across quantity water applied as irrigation was tested. Our interpretation is that TU and OSA have potential efficacy in alleviation of water stress by efficient use of water through relative water content, modulating canopy temperatures and enhanced total soluble sugars and source and sink which were crucial for gaining total biomass and seed yield under water stress conditions. The overall percent yield increment with application of TU and OSA was 9 and 6 % under irrigated condition, 19 and 18% and under moderate stress condition 17 and 12 % under severe stress conditions and water productivity 0.12- 0.10 Mg h⁻¹ with TU, 0.13-0.09 Mg h⁻¹ with OSA

at fully irrigated and medium stress; 0.11-0.03 Mg h⁻¹ with TU, 0.12-0.03 Mg h⁻¹ with OSA at severe stress conditions. Our major finding was that TU and OSA has various degrees of potential efficacy in alleviation of water stress by efficient use of water through relative water content, modulating canopy temperatures and enhanced total soluble sugars and sink partition are essential for enhanced yield and water productivity under deficit quantity of irrigation applied. Our interpretation that TU and OSA exogenous foliar application enhanced grain yield in NAIW 301, NAIW 34 with TU and LOK1, PBW 550, HD2189 with OSA with and water productivity in all wheat cultivars tested and particularly with TU in LOK1, PBW 550 and HD2189; with OSA in NIAW 301, NIAW 34 at medium and severe water stress intensities.

ACKNOWLEDGEMENT

The authors gratefully acknowledged the support provided in procuring seed material by Dr. J Rane, Dr. S. K. Bal, Dr K.K. Meena and Wheat Research Station at NIPHAD, MPKV, Rahuri for two NIAW cultivar seeds and PAU, Ludhiana, India for PBW 550 breeder seeds. The work was supported by the ICAR-NIASM with a grant under Institutional Project.

REFERENCES

- Amin, A.A., Abd El-Kader, A.A., Shalaby, M.A.F., Gharib, F.A.E., El-Sherbeny, M. Rashad, Jaime, A., Silva, T., 2013.** Physiological effects of Salicylic acid and Thiourea on growth and productivity of maize plants in sandy soil. *Commun. Soil Sci. Plant Anal.* 44, 1141-1155.
- Chen, W., Yao, X., Cai, K., Chen, J., 2010.** Silicon alleviates drought stress of rice plants by improving plant water status, photosynthesis and mineral nutrient absorption. *Biol. Trace Elem. Res.* 142, 67-76.
- DuBois, M., Gilles, K., Hamilton, J., Rebers, P., Smith, F., 1956.** Colorimetric method for determination of sugars and related substances. *Anal. Chem.* 28,350–356.
- Farooq, M.A., Saqib Z. A., Akhtar J., Bakhat H. F., Ratna-Kumar P., Dietz K. 2015:** Protective role of silicon (Si) against combined stress of salinity and boron (B) toxicity by improving antioxidant enzymes activity in rice. *Silicon*, DOI 10.1007/s12633-015-9346-z
- Farooq, M., Wahid, A., Kobayashi, N., Fujita, D., Basra, S.M.A., 2009.** Plant drought stress: effects, mechanisms and management. *Agron. Sustain. Dev.* 28, 185-212.

- Gurmani, A.R., Bano, A., Ullah, N., Khan, H., Jahangir, M., Flowers, T.J., 2013.** Exogenous abscisic acid and silicon promote salinity tolerance by reducing sodium transport and bypass flow in rice (*Oryza sativa indica*). *Aus. J. Crop Sci.* 7, 1219-1226.
- Hattori, T., Inanaga, S., Araki, H., An, P., Morita, S., Luxova, M., Lux, A., 2005.** Application of silicon enhanced drought tolerance in Sorghum bicolor. *Physiol. Plant* 123, 459-466.
- Hattori, T., Sonobe, K., Araki, H., Inanaga, S., An, P., Morita, S., 2008.** Silicon application improves water uptake by sorghum through the alleviation of stress-induced increase in hydraulic resistance. *J. Plant Nutr.* 31, 1482–1495.
- Hernández –Nistal, Aldasoro, J.J., Rodriguez, D., Matilla, A., Nicol, G., 1983.** Effect of thiourea on the ionic content and dark fixation of CO₂ in embryonic axes of *Cicer arietinum* seeds. *Physiol. Plant* 57, 273-27
- Jensen, K.B., Asay, K.H., Waldron B.L., 2001.** Dry matter production of orchard grass and perennial ryegrass at five irrigation levels. *Crop Sci.* 41, 614-619.
- Jisha, K.C., Vijayakumari, K., Puthur, J.T., 2013.** Seed priming for abiotic stress tolerance: an overview. *ActaPhysiol Plant* 35, 1381–1396.
- Kaya, C., Tuna, L., Higgs, D. 2006.** Effect of silicon on plant growth and mineral nutrition of maize grown under water stress conditions. *J. Plant Nutr.* 29, 1469-1480.
- Kjelgren, R., Cerny, K.T, 2006.** Evaluating a line source irrigation system for determining water requirements of herbaceous perennials. *J. Environ. Hort.* 24, 225-229.
- Kumar, A., Elston, J., 1992.** Genotypic differences in leaf water relations between *Brassica juncea* and *B. napus*. *Ann. Bot.* 70, 3–9.
- Mani, F.,Bettaieb, T., Zheni, K., Doudech, N., Hannachi, C., 2013.** Effect of thiourea on yield and quality of potato (*Solanum tuberosum L.*). *J. Stress Physiol. Biochem.* 1, 87-95.
- Mason, R.E., Singh, R.P., 2014.** Considerations when deploying canopy temperatures to select high yielding wheat breeding lines under drought and heat stress. *Agron.* 4, 191-201.
- Mathur, N., Singh, J., Bohra, S., Vyas, A., 2006.** Improved productivity of mung bean by application of thiourea under arid conditions. *World J. Agric. Sci.* 2, 185-187.

- McCormick, J., Johnstone, R.M., 1990.** Evidence for an essential sulfhydryl group at the substrate binding site of the A. System transport of Ehrlich cell plasma membranes. *Biochem. Cell Bio.* 68, 512-519.
- Meena, V.D., Dotania, M.L., Coumar, V., Rajrmdiran, S., Kumar, A., 2013.** A Case for Silicon Fertilization to Improve Crop Yields in Tropical Soils. *Proc. Natl. Acad. Sci., India, Sect. B Biol. Sci.*
- Miao, B.H., Han, X.G., Zhang, W.H., 2010.** The ameliorative effect of silicon on soybean seedlings grown in potassium deficient medium. *Ann. Botany* 105, 967-973.
- Peel, M.D., Asay, K.H., Johnson, D.A., Waldron, B.L., 2004.** Forage production of sainfoin across an irrigation gradient. *Crop Sci.* 44(2), 614-619.
- Pei, Z.F., Ming, D.F., Liu, D., Wan, G.L., Geng, X.X., Gong, H.J., Zhou, W.J. 2010.** Silicon improves the tolerance of water deficit stress induced by polyethylene glycol in wheat (*Triticum aestivum* L.) seedlings. *J. Plant Growth Regul.*29, 106-115.
- Rahman, M. A., Karim, A. J. M. S., Solaiman, A. R. M., Haque, M. M. and Saifuddin, K. M. 1999.** Water use, yield and yield component of wheat under irrigation and nitrogen application in terrace soil of Bangladesh. *Ann. Bangladesh Agric.* 9, 191–204.
- Rao, S.S., Regar, P.L., Tanwar, S.P.S, Singh, Y.V., 2013.** Wheat yield response to line source sprinkler irrigation and soil management practices on medium-textured shallow soils of arid environment. *Irrig. Sci.* 31, 1185–1197.
- Ratnakumar, P., Deokate, P.P., Rane, J., Jain, N., Kumar, V., Drick, V., Minhas, P.S., 2015.** Effect of stabilized silicic acid foliar sprays on wheat (*Triticum aestivum*) under water stress condition. *Proc. Nat. Acad. Sci. India Sec. Biol. Sci.* (in press).
- Rizwan, M., Meunier, J.D., Miche, H., Keller, C., 2012.**Effect of silicon on reducing cadmium toxicity in durum wheat (*Triticum turgidum* L. cv. *Claudio W.*) grown in a soil with aged contamination. *J. Hazard. Mater.* 209-210, 326-334DOI: 10.1016/j.jhazmat.2012.01.033
- Sahu, M. P., Solanki, N. S., Dashora, L. N., 1993.** Effects of thiourea, thiamine and ascorbic acid on growth and yield of maize (*Zea mays* L.). *J. Agron. Crop Sci.* 171, 65–69.

- Sahu, M.P., and Solanki, N.S., 1991.** Role of sulphhydryl compounds in improving dry matter partitioning and grain production in maize (*Zea mays* L.) J. Agron. Crop Sci. 167(5), 356-359
- Sahu, M.P., Kumawat, S.M., Ramaswamy, N.K., D'souza, S.F., 2006.** Sulphydrylbioregulator technology for increasing wheat productivity. Research bulletin RAU-BARC, 1–56.
- Sahu, M.P., Singh, D., 1995.** Role of thiourea in improving productivity of wheat (*Triticum aestivum* L.) J. Plant Growth Regul.14, 169-173.
- Singh, R.B., Chauhan, C.P.S., Minhas, P.S., 2009.** Water production functions of wheat (*Triticum aestivum* L.) irrigated with saline and alkali waters using double-line source sprinkler system. Agr. Water Manage. 96, 736–744.
- Srivastava, A.K., Ramaswamy, N.K., Mukopadhyaya, R., Jincy, M.G.C., D'Souza, S.F., 2009.** Thiourea modulates the expression and activity profile of mtATPase under salinity stress in seeds of *Brassica juncea*. Ann. Bot.103(3), 403–410.doi: 10.1093/aob/mcn229
- Tuna, A.L., Kaya, C., Higgs, D.E.B., Murillo-Amador, B., Aydemir, S., Girgin, A.R., 2008.** Silicon improves salinity tolerance in wheat plants. Environ. Exp. Bot. 62, 10-16.
- Wahid, A., Perveen, M., Gilani, S., Basra, M.S.A., 2007.** Pretreatment of seeds with H₂O₂ improves salt tolerance of wheat seedlings by alleviation of oxidative damage and expression of stress proteins. J. Plant Physiol. 164,283-294.
- Winward, T.W., Hill, R.W., 2007.** Catch-can performance under a line-source sprinkler. A. Soc. Agric. Biol. Engineers 50(4), 1167-1175.
- Yin, L., Wang, S., Li, J., Tanaka, K., Oka, M., 2013.** Application of silicon improves salt tolerance through ameliorating osmotic and ionic stresses in the seedlings of *Sorghum bicolor*. Acta Plant Physiol. 35, 3099-3107.