Journal of the Indian Society of Remote Sensing (June 2021) 49(6):1427–1438
https://doi.org/10.1007/s12524-021-01325-6

RESEARCH ARTICLE

Spectral Signature-Based Water Stress Characterization and Prediction of Wheat Yield under Varied Irrigation and Plant Bio-regulator Management Practices

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Received: 7 June 2019 / Accepted: 1 February 2021 / Published online: 20 February 2021

Abstract

Canopy reflectance based spectral indices help in effective irrigation scheduling of wheat for optimization of yield in water-scarce regions. A field experiment for two consecutive years (2013 to 2015) was conducted to evaluate the responses of wheat crop to exogenous application of plant bio-regulators (PBRs) in the water-scarce Deccan region of India (Baramati, Pune, Maharashtra). We predicted grain and biomass yields of wheat using water stress-sensitive spectral indices under varied water regimes. The water regimes were seven levels of irrigation water (equaling to 1.00, 0.85, 0.70, 0.55, 0.40, 0.25 and 0.10 times of cumulative open pan evaporation, CPE) and applied using a line-source sprinkler system). There were five PBRs, viz. thiourea, salicylic acid, potassium nitrate, gibberellin and *ortho*−silicic, with concentration 10 mM, 10 μM, 15 g L^{-1}, 25 ppm and 8 ppm, respectively, applied at various growth stages, namely crown root initiation, flag leaf and seed milking stages. Water stress indices were computed from spectral reflectance pattern recorded at different crop growth stages using ASD FieldSpec-4 Spectroradiometer (350–2500 nm). The PBRs significantly influenced the canopy reflectance pattern and maintained superior values of water stress indices over the control (without PBRs) by stabilizing leaf pigments and water contents, controlling the stomatal opening and better water use.

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Among the five PBRs, thiourea and salicylic acid mitigated water stress better and improved overall grain yield (4.6–17.5%) and total biomass (3.6–15.3%). There was no significant ($p < 0.05$) variation in both yields (grains and biomass) up to IW: CPE 0.70, indicating that irrigation scheduling at 0.70 IW: CPE could be a better option rather than full irrigation in water-scarce areas. At flowering and milking stages, all spectral indices were correlated significantly with the wheat yields. Thus, these stages could be considered as more water-sensitive stages during entire wheat growth period. Regression models based on WI and NWI-2 accounted for 92% and 78% variation in the observed yields for grain and biomass, respectively, with minimum root-mean square error. Hence, to predict the grain and biomass yields of wheat, regression models based on WI and NWI-2 at milking stage can be used successfully.

Keywords Canopy spectral reflectance · Line-source sprinkler system · Plant bio-regulators (PBRs) · Water stress indices · Wheat · Yield predictions

Introduction

Wheat (*Triticum aestivum* L.) is one of the first crops cultivated in the world and known for its adaptability to wider range of climatic conditions and contributes more than 29% of the world food grain production. In India, it is the second largest crop after rice in terms of acreage, production, consumption and contribution to national pool of food security (Anonymous 2015). Availability of irrigation water and prevalent weather plays a pivotal role in sustaining wheat productivity since most of it is cultivated under irrigated regions (Bal et al. 2004; Bal and Minhas 2017). However, wheat productivity in semi-arid Deccan plateau of India is limited by inadequate water supplies, irregular rainfall distribution (Saha et al. 2015) and soil moisture deficit coupled with problem of improper irrigation scheduling. These situations lead to mid-season water stress affecting growth and yield in wheat (Bian et al. 2016; Bukhat 2005). Water stress reduces the numbers of tillers per plant by increasing mortality, pollination in anthesis, grains per spike, grain weight and biomass yield if it occurs during cropping period (Nouri et al. 2011). Therefore, detection of water-sensitive critical growth stages in wheat is very important.

Optimizing water requirement of wheat without any yield penalty in water-deficit regions, detail know-how of crop water requirement (CWR) and irrigation scheduling for production maximization are necessities (Choudhury et al. 2013; Ratnakumar et al. 2016). For this reason, line-source sprinkler (LSS) system, an irrigation tool, is used extensively to evaluate crop yields' responses to variable level of water applications and optimize water requirement of various crops (Bal et al. 1999; Kjelgren and Cerny 2006; Singh et al. 2009; Wakchaure et al. 2016a, b). Recently, foliar application of plant bio-regulators (PBRs) in addition to irrigation water is being used as one of the key strategies to reach nearer to yield potential and stabilize wheat yield in semi-arid regions. As per several reports (Wakchaure et al. 2016a, b), PBRs impart stress tolerance and improve crop yield by regulating physiological processes and plant–water functions. However, most of the PBRs including salicylic acid (Wakchaure et al. 2016a, b), thiourea (Bhunia et al. 2015), potassium nitrate (Gimeno et al. 2014), gibberellin and *ortho*−silicic acid (Ratnakumar et al. 2016) were tried under controlled conditions to test their viability. So far, information on relative responses of PBRs to water stress-sensitive growth stages and yields of wheat at field conditions is lacking. Therefore, there is a need to evaluate the wheat responses to PBRs under water-deficit regions like Deccan Plateau using suitable water stress indices. This will not only support to characterize water stress in wheat but also to find out the water-sensitive growth stages in advance, optimizing water requirement for efficient irrigation scheduling and identifying the beneficial role of PBRs in improving grain yield productivity.

Several approaches are in use to measure water stress in wheat based on field sampling methods (Jones 2007), and those are observations of phenotypic and physiological characteristics like stomatal conductance (Wanget al. 2015), relative leaf water content (Slatyer 1967), plant water potential, chlorophyll content (Bukhat 2005), canopy and air temperature differences (Ehrler et al.1978) and crop water stress indices (CWSI) based on vapor pressure deficit (VPD) (Nanda et al.2018). Some of these approaches are laborious, time-consuming, destructive and fail for real-time evaluation. However, spectral reflectance is a non-destructive and instantaneous method used effectively for characterizing the water stress in crops (Davidson et al. 2006; Chen et al. 2005; Bandyopadhyay et al. 2014). The fundamental basis for canopy reflectance spectra depends on plant traits like physical structure, biochemical composition and water content, which in turn affect the absorption characteristics of specific wavelength of the spectrum (Sarlikioti et al. 2011; Champagne et al. 2003; Singh et al. 2013; Choudhury et al. 2019). Change in plant water status affects the reflectance in the near-infrared (NIR, 750–1300 nm) and short-wave infrared (SWIR, 1300–2500 nm) regions and thus is used in monitoring water stress. Variation in soil moisture regimes along with plant type and leaf anatomy influences sensitivity to spectral reflectance. Spectral reflectance increases as much as 70% at wavelengths of 1420 and 1900 nm when leaf water content decreases from water stress condition. However, under water stress-free conditions with higher leaf water content and relatively thicker in anatomy, the leaf response to SWIR region diminishes because of water's large absorption coefficients at this wavelength region (Ustin et al. 2012). Ray et al. (2007) reported five bands falling in the visible and NIR regions (540, 610, 630, 700 and 1000 nm) sufficiently differentiated water-stress conditions from differential irrigation treatments in potato crop by measuring the leaves and canopy reflectance. Babar et al. (2006) proposed two normalized water indices, NWI-1 ([R970 − R900]/[R970 + R900]) and NWI-2 ([R970 − R850]/[R970 + R850]) for screening genotypes of wheat under irrigated and water-deficit conditions. These indices were based on the water index WI (R_{970}/R_{900}) reported by Penuelas et al. (1993). Two more water indices NWI-3 ([R970 − R880]/ [R970 + R880]) and NWI-4 ([R970 − R920]/[R970 + R920]) were reported by Prasad et al. (2007) for screening genotypes of rainfed wheat. Therefore, in our study, we concentrated in evaluating spectral reflectance behavior of wheat crop under differential irrigation regimes based on indices developed on NIR region of spectra. Bandyopadhyay et al. (2014) characterized water stress in wheat under varied N treatments using different spectral indices and suggested possible validation to predict the wheat yields.

In the above context, the present study was carried out with the following objectives: (i) to assess wheat responses for different PBRs under varied water stress conditions using suitable spectral indices, (ii) to identify the water stress-sensitive growth stages for deriving indices, (iii) to use the derived indices for predicting the grain and biomass yield of wheat.

Materials and Methods

Climate and Soil of the Experimental Site

Experiments in the field were conducted for two consecutive years during 2013−2014, 2014−2015 at the Institute Farm of ICAR-National Institute of Abiotic Stress Management, Baramati, Pune, Maharashtra, India (18°09′30.62″N, 74°30′03.08″E, MSL 570 m). The region is relatively dry and receives an average annual rainfall of 560 mm, 91% of which is received from June to December. The monthly average summer and winter temperature hovers between 31 °C and 22 °C, respectively (Table 1). Soil type of the experimental site is medium black (sand, silt and clay, 56, 8, 36%, respectively), alkaline (pH, 8.4), low in EC (0.24 dS m^{-1}), soil organic carbon (0.63%) while low in available nitrogen (170 kg ha^{-1}), phosphorus (17 kg ha^{-1}) and potassium (140 kg ha^{-1}) contents.

Experimental Set-Up Details, Grain Yield and Biomass Estimation

A line-source sprinkler (LSS) system with eight sprinklers spaced at 6.1 m was placed in the experimental field in such a way to provide linearly decreasing water distribution pattern with approximately 25m wetted diameter under 300 kPa pressure (Figs. 1, 2). The maximum (19 mm h^{-1}) and minimum (0.5–0.8 mm h^{-1}) amount of water was delivered near the main line and at a radius of 12.2 m, respectively. The experimental plot (24.4 × 24.4 m^2) was divided into main plots of 12 × 2 m^2 size along the LSS system and further divided into sub-plots (2.0 × 1.7 m^2). The experiment was replicated four times, and statistical design was split plot with five plant bio-regulators (PBRs) and control as the main plot and seven irrigation levels as sub-plot treatments. Foliar sprays of PBRs including thiourea (TU), salicylic acid (SA), potassium nitrate

Table 1 Weather parameters (rainfall, CPE, air temperature) during growing season of wheat in 1st (2013−2014) and 2nd (2014−2015)

Month	Average Tmax (°C)		Average Tmin (°C)		Total rainfall (mm)		Total CPE (mm)	
	1st	2nd	1st	2nd	1st	2nd	1st	2nd
November	30.1	29.8	13.9	16.5	1.4	44.0	115.2	104.8
December	28.5	28.4	12.0	11.8	1.4	7.6	108.3	112.7
January	28.7	28.3	13.0	12.0	0.0	0.1	110.9	119.6
February	30.3	32.2	13.3	12.9	0.6	0.0	166.4	165.6
March	31.3	32.8	9.8	13.3	0.0	22.0	16.7	10.5
Mean/Total	29.8	30.3	12.4	13.3	3.4	73.7	517.5	513.1

*CPE cumulative pan evaporation

Fig. 1 Wheat crop grown in experimental field under line -source sprinkler system

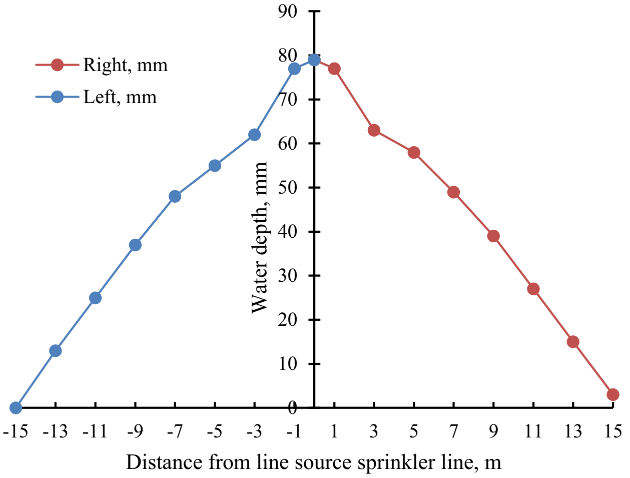


Fig. 2 Variable irrigation levels created using line -source sprinkler system

(KNO_3) and gibberellic acid (GA_3) and *ortho*−silicic acid (OSA) with concentration of 10 mM, 10 µM, 15 g L^{-1}, 25 ppm, 8 ppm, respectively, were applied at crown root initiation (CRI), flag leaf and seed milking stages in the main plots along with control where no PBR was applied. Irrigation was applied based on the ratio of cumulative pan evaporation (CPE, cm) and irrigation water (IW, cm) in seven levels using the line-source sprinkler system (Table 3). The maximum irrigation water varied between 6.5 and 7.4 cm (IW: CPE, 1.0) at each irrigation, which was equivalent to CPE and other levels of irrigation water applied decreased linearly with IW: CPE of 0.85, 0.70, 0.55, 0.40, 0.25 and 0.10, respectively, along the sub-plots. Further, these water levels of IW: CPE 1.00–0.70, 0.69–0.40, 0.39–0.10 were rated as no stress, medium stress and severe stress, respectively (Table 2). After initial field preparation, wheat cultivar HD 2189 was sown by drill with a seed rate of 100 kg ha^{-1} perpendicular to the main LSS system in row spacing of 22.5 cm on Nov 02 and Nov 04 in 2013 and 2014, respectively. It was followed by a common irrigation of 5.7–6.1 cm for better germination and crop establishment. In total, 60 kg P_2O_5 and 40 kg K_2O were drilled during sowing, while nitrogen was applied in three splits at sowing (60 kg), CRI (30 kg) and flag leaf stage (30 kg).

The grain yield and biomass from each sub-plot were measured after manual harvesting of wheat at maturity. The harvested plant samples were placed in hot air oven and dried to constant weight at 60 °C for 24 h for obtaining the grain and biomass yield (Wakchaure et al. 2020).

Reflectance Measurements

The canopy reflectance (spectral range: 350–2500 nm, 1 nm band width) was measured using handheld ASD spectroradiometer (Fieldspec − 4, USA) on days with bright sunshine between 1100 and 1300 h with field of view (FOV) kept as 25°. To maintain the ground coverage uniform as 44 cm for the equipment, the distance between the optical head of the spectroradiometer and top of the plant was kept as 1 m for all observations. A spectral on white panel was used to get reference signal before the canopy reflectance measurement for optimization of the spectroradiometer. For computation of the canopy reflectance, the ratio of canopy radiances and the radiance from the white reference panel was used.

The spectral signatures of wheat canopy were recorded during major phenological stages, viz. booting, flowering, milking, soft dough and harvesting stages, during both

Table 2 Formulae for spectral reflectance indices calculated at different phenological stages

Sr. No.	Description	Spectral index	Formula	Author
1	Water index	WI	R970/R900	Peñuelas et al. (1993)
2	Normalized water index-1	NWI-1	(R970–R900)/(R970 + R900)	Babar et al. (2006)
3	Normalized water index-2	NWI-2	(R970–R850)/(R970 + R850)	Babar et al. (2006)
4	Normalized water index−3	NWI-3	(R970–R920)/(R970 + R920)	Prasad et al. (2007)
5	Normalized water index-4	NWI-4	(R970–R880)/(R970 + R880)	Prasad et al. (2007)

Where R and the subscript numbers indicate the light reflectance at specific wavelength (nm)

Table 3 Total amount of irrigation applied and days of irrigation application to wheat under different irrigation treatments

Treatment IW: CPE	Amount of water applied with line-source sprinkler system (LSS, cm)		Total water, cm	
	2013–2014	2014–2015	2013–2014	2014–2015
I1 (1.00)	33.1	35.7	39.1	47.0
I2 (0.85)	28.2	30.1	34.2	41.4
I3 (0.70)	23.3	24.9	29.3	36.2
I4 (0.55)	18.4	19.3	24.2	30.3
I5 (0.40)	13.1	14.3	19.1	25.6
I6 (0.25)	8.4	8.9	14.4	20.2
I7 (0.10)	3.2	3.6	9.2	14.9
Irrigation (DAS)	15, 32, 51, 72, 89	17, 36, 58, 77, 92		

Total water: LSS + rainfall (RF) + common irrigation (CI)

years, and spectral reflectance indices were determined using indices as reported in Table 2.

Statistical Analysis

The experimental data were analyzed using statistical program SAS (Gomez and Gomez 1984). The statistical significance of the treatments' effect and the significance of difference between means of two treatments were determined using Duncan's multiple range test and least significant differences (LSD) at 5% probability, respectively. Plots, correlations and regressions equations including weather and crop yield data were developed using MS Excel pack.

Results and Discussion

Grain and Biomass Yield of Wheat

Wheat grain and biomass yield were significantly ($P < 0.05$) affected by levels of irrigation and foliar application of PBRs during both the years (Tables 4, 5). The overall yields were higher in the year 2013–2014 as compared to 2014–2015. The highest average grain yield (4422.6 kg ha^{-1}) was obtained at IW: CPE 0.85 and decreased to 936.8 kg ha^{-1} linearly with reduction in quantities of water applied; the yield could be sustained until IW: CPE 0.70. This indicates that irrigation at 0.70 IW: CPE can be considered as threshold for achieving water economy in this region. Similar response of grain yield to irrigation water has been reported in Vertisol (Bal et al. 2004; Bandyopadhyay et al. 2010) and shallow

Table 4 Grain and biomass yield of wheat as affected by irrigation levels

Treatment Irrigation levels (IW: CPE)	Grain yield (kg/ha)			Biomass yield (kg/ha)		
	2013–2014	2014–2015	Pooled	2013–2014	2014–2015	Pooled
1.00	4449.0b	3822.1b	4135.6b	12,562.6a	10,890.5a	11,726.5b
0.85	4811.3a	4033.9a	4422.6a	12,797.8a	11,051.4a	11,924.6a
0.70	4798.4a	4008.5a	4403.4a	12,781.5a	11,003.2a	11,892.4a
0.55	3953.3c	3523.1c	3738.2c	11,194.7b	10,616.5b	10,905.6c
0.40	3014.1d	2689.2d	2851.6d	9714.7c	9456.3c	9585.5d
0.25	2067.6e	1700.6e	1884.1e	7804.7d	7066.6d	7435.6e
0.10	1095.3f	778.3f	936.8f	4740.2e	3505.7e	4122.9f
LSD (p = 0.05) IW: CPE	106.4	94.2	79.0	304	357	191

Duncan multiple range test (DMRT, $p = 0.05$) results represent that values in a column followed by similar letters are not significantly different

Table 5 Grain yield and biomass yield of wheat as affected by plant bio-regulators (PBRs)

Plant bio-regulators	Grain yield (kg/ha)			Biomass yield (kg/ha)		
	2013–2014	2014–2015	Pooled	2013–2014	2014–2015	Pooled
TU	3789a	3130a	3460a	11340a	9520a	10430a
SA	3590b	3039b	3315b	10680b	9290ab	9985b
KNO_3	3467c	2951c	3210c	10120c	9120bc	9620c
GA3	3351d	2948c	3150c	9870 cd	9090c	9480c
OSA	3333d	2847d	3090d	9830d	8910d	9370d
No PBR	3204e	2705e	2955e	9530e	8560e	9045e
LSD($p = 0.05$) PBR	114.1	87.1	88.9	312	338	139
IW × PBRs	260.6	230.8	193.5	760	830	480

Duncan multiple range test (DMRT, $p = 0.05$) results represent that values in a column followed by similar letters are not significantly different

Fig. 3 Relative response of plant bio-regulators (PBRs) and irrigation levels in wheat crop

medium-textured soils of arid environment (Rao et al. 2013).

The grain yield of wheat was significantly influenced when PBRs were applied exogenously. The averaged (two years) grain yield was improved by 4.6 to 17.1% on application of PBRs over control (without PBR). Similarly, Pandey et al. 2013 and Wakchaure et al. 2016a, b also reported the role of PBRs (TU and SA) in improving stress tolerance, plant growth and crop yield. Similar results of beneficial role of PBRs in improving grain yields under different abiotic stressed environments were reported in Brassica with TU under salt stress (Pandey et al. 2013), in soybean under drought with SA (Hayat et al. 2010), in wheat with GA_3 under salt stress (Tuna et al. 2008) and in sorghum with KNO_3 under water stress (Wakchaure et al. 2016b).

The interaction effect of PBRs and irrigation treatments was also significant on grain yield in both the years (Table 5). Overall enhancement in grain yield with application of PBRs was 3.2–3.8, 4.0–9.8 and 23.2–68.9%, respectively, under no stress (IW: CPE 1.00–0.70), moderate stress (0.69–0.50) and severe stress (0.49 − 0.10), which is an evident of positive influence of PBRs for mitigating water stress under the water-deficit conditions. Especially, TU and SA were found to be comparatively effective under severe water stress conditions. This may be

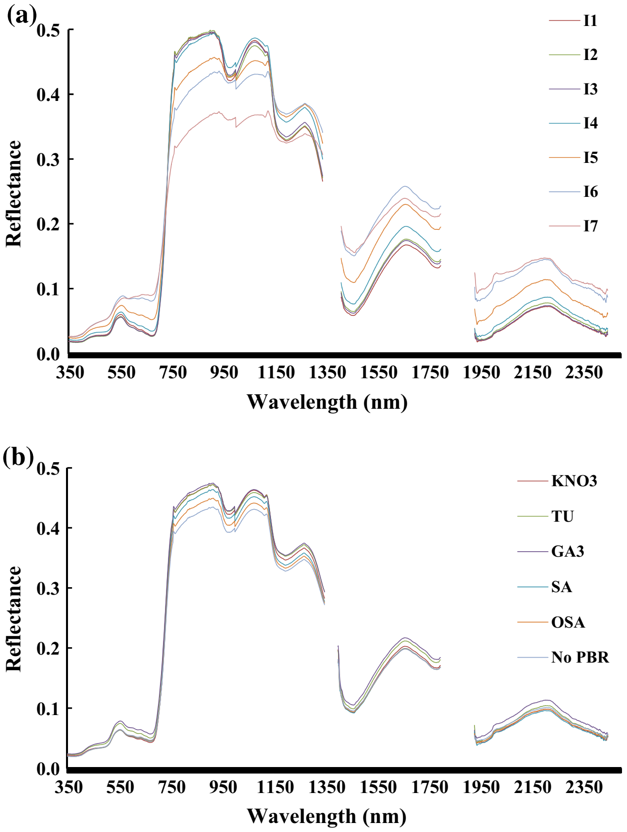


Fig. 4 Changes in canopy reflectance spectra of wheat affected by (a) irrigation and (b) plant bio-regulators (PBRs) treatments at milking stage during 2014−2015

attributed to its role in sustaining leaf water content, modulating the stomata opening and water usage (Fig. 3). Similar trend of increase (+ 3.6 to + 15.3%) in biomass yield was also observed under differential irrigation managements and PBRs. Applications of PBRs alone improved biomass yield by 3.6–15.3% over the control (no PBR).

Characterization of Plant Water Stress

Differential Irrigations and PBRs on Canopy Reflectance

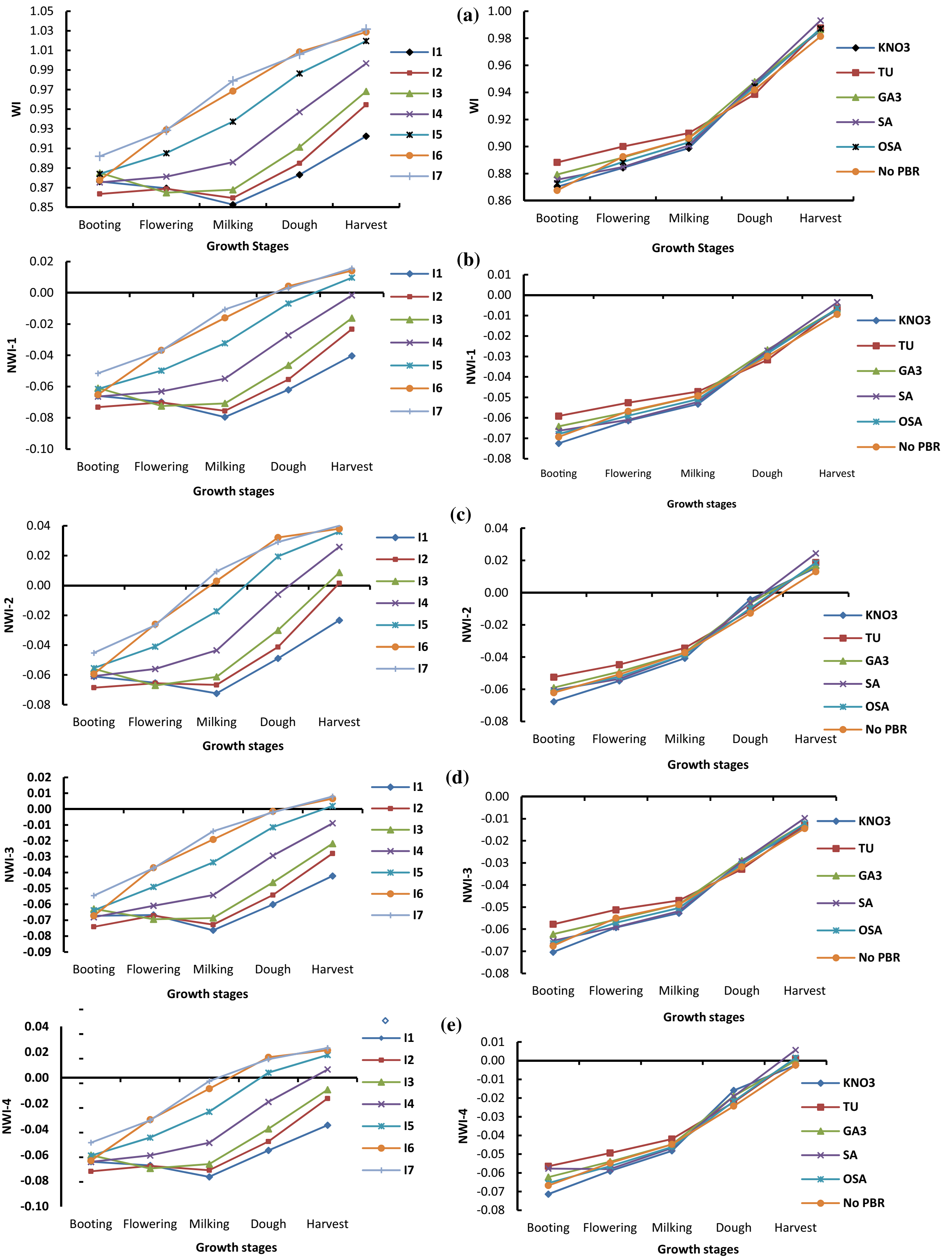
The canopy reflectance curve obtained at milking stage of wheat got significantly affected by irrigation levels and PBRs (Fig. 4) as spectral reflectance in the visible range (400 − 700 nm) increased with increase in water stress regimes. The highest values of visible reflectance spectra were noticed at severe water stress level (IW: CPE 0.10 − 0.39) than that of moderate (0.40 − 0.69) and no stress (1.00 − 0.70) levels. Similarly, foliar application of PBRs, especially TU and SA, considerably reduced the reflectance in the visible region over control, indicating that beneficial role of PBRs in improving leaf water status through closed stomata and control of cell turgor pressure is under water deficits. Increase in chlorophyll contents in wheat leaf absorbed higher incident radiation at visible range while reflecting more at near-infrared regions (Reynolds et al. 2012). Reflectance of spectra in the near-infrared region (700 − 1300 nm) at severe stress levels showed comparatively lower values than that of moderate and no stress levels. Also, spectral reflectance in the NIR region for no PBR was comparatively lower than that of PBRs. This could be recognized due to lower LAI values at water deficits and under no PBRs application (Wakchaure et al. 2016a). Among the all electromagnetic spectrum, plant canopy has strong ability to scatter photons in the NIR region. However, in the NIR region plant canopies strongly scatter photons as compared to other regions of electromagnetic spectrum (Asner 1998). In shortwave-infrared region (1300−2500 nm), the higher values of reflectance were at severe stressed levels than those of at moderate and no stress levels. Similarly, reflectance in the SWIR region was higher for PBRs than that of control (no PBRs). This may be attributed to decrease in leaf water content (Joseph 2005) with increase in water deficits and no use of PBRs (Wakchaure et al. 2016b). The same was also reported that canopy reflectance spectra pattern in the visible, NIR and SWIR regions is significantly influenced by the leaf pigment, leaf area and plant water status (Bandyopadhyay et al. 2014). However, under water stress-free conditions with higher leaf water content and relatively thicker in anatomy, the leaf response to SWIR region (beyond 1300 nm) diminishes because of water's large absorption coefficients at this wavelength region (Ustin et al. 2012).

Spectral Indices Related to Water Stress

Temporal changes in the spectral water stress indices (water index-WI and normalized water indices, NWI-1, NWI-2, NWI-3 and NWI-4) at various wheat growth stages, viz. booting, flowering, milking and harvesting, are illustrated in Fig. 5a–e. The spectral water stress indices were affected by both different PBRs and irrigation treatments. In general, values of spectral reflectance indices increased with increase in water deficits. There are an initial decrease in all reflectance indices from booting to milking stages and an increase there after toward harvesting at optimum irrigation levels (IW: CPE 0.70 − 0.10). In contrary, consistent increasing trend in reflectance indices was noticed from booting to harvest stage for moderate and severe water stress (IW: CPE 0.69 − 0.10) conditions. Similar observation was reported by Prasad et al. (2007) for wheat grown under water-deficit conditions. The foliar application PBRs was also effective in lowering the values of all spectral water stress indices over control irrespective of different wheat growth stages. Especially, foliar application of TU and SA combining with irrigation water at IW: CPE 1.00 − 0.85 resulted in lowest reflectance for all reported indices. This indicates the role of PBRs in mitigating adverse impact of water stress on wheat growth by maintaining cooler canopy temperature and leaf-water content (Wakchaure et al. 2016a).

Correlation of Spectral Water Stress Indices with Grain and Biomass Yields

Positive significant correlation among various water stress indices (WI, NWI-1, NWI-2, NWI-3 and NWI-4) was observed for wheat at milking stage. Relationship between grain yield with spectral indices showed significant ($P < 0.05$) negative correlation at all phenological stages of wheat except at booting stage (Table 6) as more water content in the canopy might has decreased the reflectance of water band (970 nm) (Thenkabail et al. 2011). The grain yield was correlated better at flowering stage for all the spectral indices. Similarly, all spectral indices were significantly ($P < 0.05$) negatively correlated with biomass at all crop stages except for NWI-3 at booting stage (Table 6). These results of spectral indices, grain and biomass yields of wheat have been similar to previous findings (Bal et al. 2013; Bandyopadhyay et al. 2014; Prasad et al. 2007). Among all spectral indices, WI showed the highest correlation coefficients (− 0.853 to –0.973) for both yields indicating their water sensitiveness at flowering, milking


(a)
WI
1.05
1.03
1.01
0.99
0.97
0.95
0.93
0.91
0.89
0.87
0.85
Booting
Flowering
Milking
Dough
Harvest
Growth Stages
I1
I2
I3
I4
I5
I6
I7
WI
1.00
0.98
0.96
0.94
0.92
0.90
0.88
0.86
Booting
Flowering
Milking
Dough
Harvest
Growth Stages
KNO3
TU
GA3
SA
OSA
No PBR
(b)
NWI-1
0.02
0.00
-0.02
-0.04
-0.06
-0.08
-0.10
Booting
Flowering
Milking
Dough
Harvest
Growth stages
I1
I2
I3
I4
I5
I6
I7
NWI-1
0.01
0.00
-0.01
-0.02
-0.03
-0.04
-0.05
-0.06
-0.07
-0.08
Booting
Flowering
Milking
Dough
Harvest
Growth stages
KNO3
TU
GA3
SA
OSA
No PBR
(c)
NWI-2
0.04
0.02
0.00
-0.02
-0.04
-0.06
-0.08
Booting
Flowering
Milking
Dough
Harvest
Growth stages
I1
I2
I3
I4
I5
I6
I7
NWI-2
0.04
0.02
0.00
-0.02
-0.04
-0.06
-0.08
Booting
Flowering
Milking
Dough
Harvest
Growth stages
KNO3
TU
GA3
SA
OSA
No PBR
(d)
NWI-3
0.02
0.01
0.00
-0.01
-0.02
-0.03
-0.04
-0.05
-0.06
-0.07
-0.08
-0.09
Booting
Flowering
Milking
Dough
Harvest
Growth stages
I1
I2
I3
I4
I5
I6
I7
NWI-3
0.00
-0.01
-0.02
-0.03
-0.04
-0.05
-0.06
-0.07
-0.08
Booting
Flowering
Milking
Dough
Harvest
Growth stages
KNO3
TU
GA3
SA
OSA
No PBR
(e)
NWI-4
0.04
0.02
0.00
-0.02
-0.04
-0.06
-0.08
-0.10
Booting
Flowering
Milking
Dough
Harvest
Growth stages
I1
I2
I3
I4
I5
I6
I7
NWI-4
0.01
0.00
-0.01
-0.02
-0.03
-0.04
-0.05
-0.06
-0.07
-0.08
Booting
Flowering
Milking
Dough
Harvest
Growth stages
KNO3
TU
GA3
SA
OSA
No PBR

◀**Fig. 5** Temporal changes in the water indices: (a) WI, (b) NWI-1, (c) NWI-2, (d) NWI-3 and (e) NWI-4 as affected by the different irrigation levels and plant bio-regulators (PBRs) during wheat growth stages

and dough stages of wheat. It was also noted that at flowering and milking stages, all reported spectral indices were significantly correlated with the wheat yields with maximum values of correlation coefficients. Thus, these stages could be considered as the most water-sensitive stages during entire wheat growth. Our findings also suggest that all these five water stress indices (WI, and NRI 1–4) derived from NIR region (880–970 nm) were correlated at equal strength ($r = \; > 0.684$) with the grain yield and biomasses of wheat under differential water stress vs. stress-free conditions. Therefore, using any one of them, preferably the simplest one WI among them can satisfactorily depict the relationship between spectral reflectance vs. water stress relationships on grain and biomass yield of wheat. Since wheat leaves are thin in thickness, therefore, water stress-sensitive vegetation indices at SWIR beyond 1400–2400 nm may be explored, particularly at extreme water-stressed conditions (Carter 1993). However, unlike water stress-sensitive vegetation indices at NIR region, use of water stress indices at SWIR region should be selectively used as they are less sensitive to plants with thicker leaves and higher in relative water content when grown under water stress-free conditions (Ustin et al. 2012).

Prediction of Grain and Biomass Yields Using Spectral Reflectance Indices

Regression models developed using the reflectance indices and grain yield recorded at milk stage in year 2013–2014 indicated that all five indices account for 94% variability in grain yield of wheat (Table 7). Similar reports are given by Prasad et al. (2007), and Bandyopadhyay et al. (2014) also reported that NWI-1, NWI-3 and NWI-4 indices are better predictors of wheat grain yield. These models were validated independently with grain yield and reflectance data sets of year 2014–2015, which accounted for 92% variation in observed wheat grain yield (Table 7). The highest

Table 6 Correlation coefficient between spectral indices at different growth stages, grain yields and biomass yields

Crop stages	WI	NWI-1	NWI-2	NWI-3	NWI-4
Grain yields					
Booting	−0.706^{NS}	−0.705 ^{NS}	−0.734 ^{NS}	−0.684 ^{NS}	−0.706 ^{NS}
Flowering	−0.973**	−0.973**	−0.970**	−0.973**	−0.971**
Milking	−0.967**	−0.964**	−0.965**	−0.964**	−0.964**
Dough	−0.912**	−0.908**	−0.901**	−0.911**	−0.908**
Harvest	−0.838*	−0.830*	−0.771*	−0.846*	−0.809*
Biomass yields					
Booting	−0.752*	−0.750*	−0.772*	−0.733 ^{NS}	−0.750*
Flowering	−0.924**	−0.923**	−0.919**	−0.925**	−0.921**
Milking	−0.924**	−0.920**	−0.923**	−0.920**	−0.921**
Dough	−0.853**	−0.848*	−0.838*	−0.853**	−0.848*
Harvest	−0.790*	−0.783*	−0.727**	−0.798*	−0.763*

NS not significantly different at $p \leq 0.05$; * Significant at $p \leq 0.05$; ** Significant at $p \leq 0.01$

Table 7 Validation of the regression models between spectral indices and grain yield (Y) of wheat

Model	Parameters	Regression equations	R^2 during calibration (2013–2014)	R^2 during validation (2014–2015)	RMSE (%)
1	WI	Y = 25,809.6–24,887.5(WI)	0.942**	0.924**	10.0
2	NWI-1	Y = 989.4–45,445.7(NWI-1)	0.937**	0.916**	10.5
3	NWI-2	Y = 1819.6–38,702.8(NWI-2)	0.938**	0.920**	10.3
4	NWI-3	Y = 764.7–50,237.1(NWI-3)	0.938**	0.917**	10.4
5	NWI-4	Y = 1353.0–42,416.3(NWI-4)	0.936**	0.918**	10.5

**Significant at $p \leq 0.01$

Table 8 Validation of the regression models between spectral indices and biomass yield (*Y*) of wheat

Model	Parameters	Regression equations	R^2 during calibration (2013–2014)	R^2 during validation (2014–2015)	RMSE (%)
1	WI	$Y = 56{,}247.4–51{,}273.7(\mathrm{WI})$	0.906**	0.784**	10.7
2	NWI-1	$Y = 5119.8–93{,}476.5(\mathrm{NWI\text{-}1})$	0.899**	0.774**	11.0
3	NWI-2	$Y = 6821.4–79{,}778.3(\mathrm{NWI\text{-}2})$	0.903**	0.782**	10.8
4	NWI-3	$Y = 4656.5–103{,}352.7(\mathrm{NWI\text{-}3})$	0.901**	0.775**	11.0
5	NWI-4	$Y = 5862.9–87{,}356.4(\mathrm{NWI\text{-}4})$	0.901**	0.777**	10.9

**Significant at $p \leq 0.01$

variation was for model − 1 (based on WI) and model − 3 (based on NWI-2). The RMSE of the predicted wheat grain yield for WI and NWI-2 models was minimum among all the models and accounted for 10.0 and 10.3%, respectively, of the mean observed grain yield, which indicates better prediction ability of wheat grain yield by using these two indices.

Similarly, regression models using spectral indices and wheat biomass yield at milking stage during the year 2013–2014 accounted for 90% variability in wheat biomass yield (Table 8). Validation report of these models with spectral indices and biomass yield of the year 2014–2015 indicated that predicted biomass yield accounted for 78% variation in observed biomass yield (Table 8). Models based on WI and NWI-2 accounted for maximum of 78% variations in the observed biomass yield. The RMSE of predicted grain yield accounted for 10.7 and 10.8% of the observed biomass yield, respectively. Therefore, WI and NWI-2-based models can be put into use for better prediction of wheat biomass yield.

Conclusion

This study found that integrative use of PBRs with limited irrigation substantially enhanced grain (up to 17.5%) and biomass (up to 15.3%) of wheat under water-deficit conditions. Plant bio-regulators (PBRs) like thiourea and salicylic acid were quite effective for minimizing the negative impact of water stress in wheat fields. The irrigation scheduling at optimized IW: CPE (0.60 − 0.70) could be a better option rather than full irrigation (IW: CPE 1.00) for improving yield potential without any penalty. All the water-sensitive spectral indices were highly significant and negatively correlated with yields at most water-sensitive stage—flowering and milking stages of wheat. Therefore, instead of five water stress indices derived from NIR region, we suggest use of only the simplest and better correlated index, i.e., water index (R970 / R900) for spectral evaluation of wheat performance under varying water-deficit regimes. Validation report of regression models based on WI and NWI-2 accounted for maximum 92% and 78% variability in observed grain and biomass yields of wheat with minimum RMSE, respectively. Therefore, regression models based on WI and NWI-2 verified at milking stage can be effectively used to predict wheat yields well in advance.

Acknowledgements Authors are thankful to the Director, ICAR-National Institute of Abiotic Stress Management (NIASM), Baramati, Pune, India, and Indian Council of Agricultural Research, New Delhi, India, for the support of the research grant under which the study was taken. Authors also gratefully acknowledge the guidance and help of other scientists/technicians during the conduct of the experiment.

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