



Moisture-stress management under limited and assured irrigation regimes in wheat (*Triticum aestivum*): Effects on crop productivity, water use efficiency, grain quality, nutrient acquisition and soil fertility

R S BANA¹, SEEMA SEPAT², K S RANA³, V POONIYA⁴ and ANIL K CHOUDHARY⁵

ICAR–Indian Agricultural Research Institute, New Delhi 110 012

Received: 04 May 2018; Accepted: 22 June 2018

ABSTRACT

A field experiment was carried-out for three consecutive years during winter seasons of 2010–11 to 2012–13 at ICAR–Indian Agricultural Research Institute, New Delhi to evaluate the effect of various moisture-stress management options on crop and water productivity, quality, nutrient uptake and soil fertility in wheat [*Triticum aestivum* (L.) emend Fiori and Paol]. The experiment was laid out in randomized block design with three replications comprising eight treatments, viz. Pusa hydrogel under assured irrigation (PHAI), organic mulch under assured irrigation (OMAI), aqua-sowing under assured irrigation (ASAI), control under assured irrigation (CAI), Pusa hydrogel under limited irrigation (PHLI), organic mulch under limited irrigation (OMLI), aqua-sowing under limited irrigation (ASLI), and control under limited irrigation (CLI). The maximum plant height (87.2 cm), tillers/m² (560) and LAI (5.19) were recorded with OMAI followed by PHAI and ASAI. Wheat grain yield increased by 5.9, 6.7 and 11.4% due to aqua-sowing, Pusa hydrogel and organic mulch, respectively under assured irrigation. Per cent grain yield improvement under limited irrigation was 13.2, 14.8 and 22.1% owing to aqua-sowing, Pusa hydrogel and organic mulch, respectively. The grain protein content was more under limited irrigation with maximum protein (10.33%) under CLI. Highest consumptive use (430 mm) was recorded under OMAI; however, the maximum water-use efficiency was found with OMLI (11.7 kg/ha-mm) followed by ASLI (11.4 kg/ha-mm). Under limited irrigation, the lowest proline accumulation was recorded under OMLI (9.3 µg/g fresh weight) while under PHLI and ASLI it was 10.2 and 13.1 µg/g fresh weight, respectively. Overall, it is highlighted that under limited irrigation, the organic mulching followed by Pusa hydrogel and aqua-sowing can be good options to achieve higher crop and water productivity and nutrient acquisition in wheat under water starved agro-ecosystems.

Key words: Aqua-sowing, Limited irrigation, Moisture-stress management, Organic mulch, Pusa hydrogel, Wheat

Globally, India is the second largest producer of wheat [*Triticum aestivum* (L.) emend Fiori and Paol] having an acreage of 30.2 m ha with total wheat production of 93.5 mt (MoA and FW 2016-17). Wheat productivity in India is 3.09 t/ha which is far less than the developed nations and the climatic potential of the country. Though, more than 90% of wheat area in India is irrigated (MoA and FW 2016-17), but only around 1/3rd area receives desired irrigation and rest of the area is under limited irrigations since the crop receives only 2–3 irrigations (Shinde 2011). Sub-optimal irrigation supply results in soil moisture-stress at critical growth stages and consequently leads to poor yields (Choudhary *et al.* 2010, Rana and Bana 2012).

Further, fresh water demand in the country is anticipated to increase 2.3 times by 2050 (Chattaraji *et al.* 2011). Thus, water scarcity scenario is expected to be more acute in near future particularly the water needs for irrigation. Therefore, proper management of irrigation water and soil moisture is highly essential for reducing moisture-stress and increasing crop production specifically under water-deficient ecologies (Kumar *et al.* 2015).

There are several options for *in-situ* soil moisture conservation or management which may have stress-diminishing effect on wheat besides providing favourable crop micro-climate. Organic mulching, aqua-fertilization sowing and application of synthetic polymers are some of the suggested pathways for efficient moisture management (Choudhary *et al.* 2008). Crop residues if applied as mulch are well known to conserve the rhizospheric moisture besides reducing weed growth, improving soil health and moderating effect on soil temperature. This might be achieved if the fields could be mulched when the soil profile is wet (Acharya *et al.* 1998, Bamboriya *et al.* 2017).

¹Scientist (e mail: rsbana@gmail.com), ²Scientist (e mail: seemasepat12@gmail.com), ³Principal Scientist (e mail: ksrana04@yahoo.com), ⁴Scientist (e mail: vpooniya@gmail.com); ⁵Senior Scientist (e mail: anilhpau2010@gmail.com), Division of Agronomy.

Aqua-fertilization sowing which consists of administering small quantum of water + nutrient solution in the root zone while seeding also can be of immense importance to reduce moisture-stress during establishment phase of crop ontogeny (Rana and Singh 2006, Rana and Bana 2012). Moreover, aqua-sowing also facilitates mobilization of nutrients in the soils, uniform germination, higher nutrient uptake and improved water-use efficiency (Rana and Bana 2012, Singh *et al.* 2005). Similarly, Pusa hydrogel – a natural, bio-degradable, cellulose based superabsorbent polymer absorbs water, a minimum of 350 times of its weight, and releases the moisture to the crop when it comes under stress (Bana *et al.* 2013). Hydrogels potentially influence different soil properties such as infiltration rates, bulk density, soil structure, compaction and aggregate stability (El-Hady and Abo-Sedera 2006), and also affects the evaporation rates (Taban and Naeini 2006). It is well documented that addition of hydrogel improves availability of water to plants by polymer swelling mechanism owing to reduced hydraulic conductivity. Consequently it leads to reduced percolation of water and thereby increased retention pores (El-Hady and Abo-Sedera 2006). Use of hydrogels for raising field crops, particularly under moisture stress ecologies could be a viable option if they are applied in smaller quantities at shallow depths in rows just below the seeds (Narjary and Aggarwal 2014). Several independent studies are carried out on these moisture-stress management options under moisture stress environments. Little information is available on the comparative assessment of these technologies under varied moisture regimes. Keeping these points in view, a field study was conducted with the aim to evaluate the response of wheat to various moisture management practices under assured as well as limited irrigation regimes and the effects on wheat productivity, nutrient uptake, quality and water use-efficiency.

MATERIALS AND METHODS

A field experiment was carried out during 2010–11 to 2012–13 at fixed site of ICAR–Indian Agricultural Research Institute, New Delhi (Latitude 28°40'N; Longitude 77°12'E; Altitude 228.6 m). New Delhi has a semi-arid and sub-tropical climate with hot dry summers and severe cold winters. The mean annual rainfall is about 650 mm, of which nearly 80% is received during south–west monsoon period (July–September) and the rest during the period between October to May. The mean daily U.S. Weather Bureau Class 'A' open pan evaporation value reaches as high as 10.9 mm in the June month and as low as 1.5 mm in January month. The annual pan evaporation is about 850 mm. The mean wind velocity varies from 3.5 km/hr during October to 7.6 km/hr during April. Mean relative humidity attains the maximum value (85 to 90% or even more) during the south–west monsoon and the minimum (30 to 45%) during the summer months. A total of 69.4, 43 and 176 mm rainfall was received during crop growing periods of 2010–11, 2011–12 and 2012–13, respectively. The physical and chemical properties of the soil in the 0–30 cm

Table 1 Physical and chemical properties of soil at the experimental site

Particulars	Values
<i>Mechanical composition (Bouyoucos 1962)</i>	
Sand (%)	61.23
Silt (%)	15.59
Clay (%)	23.25
Textural class	Sandy loam
<i>Physical properties</i>	
Bulk density (g/cm ³) (Rana <i>et al.</i> 2014)	1.57
Infiltration rate (cm/hr) (Rana <i>et al.</i> 2014)	1.26
Permanent wilting point (%) (Richards 1954)	6.5
Field capacity (% by weight) (Richards 1954)	17.6
<i>Chemical properties</i>	
pH (1: 2; Soil: water ratio) (Piper 1950)	7.6
Electrical conductivity (dS/m) (Piper 1950)	0.33
Organic C (%) (Walkley and Black 1934)	0.44
Available N (kg/ha) (Subbiah and Asija 1956)	195.8
Available P (kg/ha) (Olsen <i>et al.</i> 1954)	14.0
Available K (kg/ha) (Jackson 1973)	230.0

of soil profile at the experimental site are given in Table 1.

The experiment consisted of eight treatments, viz. Pusa hydrogel under assured irrigation (PHAI), organic-mulch under assured irrigation (OMAI), aqua-sowing under assured irrigation (ASAI), control under assured irrigation (CAI), Pusa hydrogel under limited irrigation (PHLI), organic-mulch under limited irrigation (OMLI), aqua-sowing under limited irrigation (ASLI) and control under limited irrigation (CLI). Pusa hydrogel was applied @ 2.5 kg/ha in the soil along with basal dose of NPK fertilizers. In the aqua-sowing treatment, 20000 l water/ha was poured along with the seed at the sowing time. Pearl millet residues @ 3 t/ha were retained on surface in the organic mulching treatment. Under limited irrigation conditions, the crop was irrigated twice, i.e. at crown root initiation (CRI) and flowering stage. Under assured irrigation conditions, 6 irrigations were applied at CRI, tillering, late jointing, flowering, milking and dough stages. As per the treatments, a measured amount of water was delivered to the crop by Parshall-flume. In each irrigation, 60 mm water was applied through check-basin method. The field experiment was carried out in randomized block design with 3 replications keeping plot size of 6 m × 4 m (24 m²). The wheat variety HD-2967 was used in the study. The crop was sown, after harvest of previous pearl millet crop, using seed @ 100 kg/ha at 25 cm row spacing on November 21 in 2010 and 2011 and on November 24 in 2012. The 60 kg/ha each of N, P₂O₅ and K₂O were applied as a basal dose through urea, single super phosphate and muriate of potash, respectively. Remaining half dose of N (60 kg/ha) was applied in standing crop at first irrigation coinciding with CRI stage. Seed treatment was done with Chlorpyrifos before last night of sowing of crop. Weeds

were managed by the tank-mix application of Metsulfuron methyl (@ 4 g a.i./ha) + Sulfosulfuron (@ 25 g a.i./ha) after 35 days of sowing. In order to control termite infestation Chlorpyrifos was also applied in the standing crop with first irrigation water.

At harvest, the dried wheat grain and straw samples were prepared for nutrient analysis with a milling machine with a sieve spacing of 0.7 mm. Wheat grain and straw samples were analyzed for total N using a Kjeldahl digestion unit, while total P and K were determined using a sulfuric–nitric–perchloric acid digest (Rana *et al.* 2014). Finally, the nutrient uptake were determined by multiplying dried wheat grain and straw weight yields and respective nutrient contents in the dry weight of wheat grain and straw. Total uptake was calculated by summing-up the two values, i.e. wheat grain uptake + wheat straw uptake. Crude protein content in grain was obtained by multiplying N concentration with a coefficient factor 6.25 (Rana *et al.* 2014). The proline content was measured by method of Irigoyen *et al.* (1992). The soil samples were collected from 0–15 cm soil profile at the initial and at the end of experimentation period. The soil samples were air-dried, ground and passed through 2 mm mesh sieve and were analyzed for available N, P and K. The available-N was estimated by alkaline $KMnO_4$ method, the available-P in soil by Olsen's method and available-K by neutral normal ammonium acetate extraction method as described by Rana *et al.* (2014). The data relating to each character were analyzed as per the procedure of analysis of variance and significance of randomized block design was tested by *F*-test (Sheoran *et al.* 1998). Standard error of means (SEm \pm) and critical difference (CD) at 5% level of significance were worked out for each parameter.

RESULTS AND DISCUSSION

Growth and yield

The pooled data of three years in Table 2 revealed that various moisture management practices significantly

influenced the growth yield attributes and yield in wheat crop. Under limited irrigation, significantly higher plant height, number of tillers and leaf-area index were recorded in the treatments where moisture-stress management was adopted than no-moisture stress-management (Table 2). The maximum value of these growth parameters was observed under OMAI treatment. Superior performance of this treatment may be attributed to increased soil-moisture availability due to reduced evaporative moisture losses coupled with improvement in soil moisture holding capacity owing to addition of organic matter in the soil. Further, mulching is also associated with the temperature moderation effect and reduced weed growth which consequently leads to better plant growth and development (Das *et al.* 2014, Bamboriya *et al.* 2017). The significantly better growth under Pusa hydrogel may be because it helped in conserving soil moisture by retaining soil moisture in the rhizosphere (Patil *et al.* 2014). Planting of wheat through aqua-sowing resulted in early germination and quick establishment, benefited crop by increasing nutrient availability (Rana and Bana 2012).

Different moisture-stress management techniques had favourable effect on yield attributes of wheat. From the mean value of three year data it was observed that yield attributes, viz. spikes/plant, grains/spike and spike length were significantly highest under OMAI treatment followed by PHAI and ASAI treatments in comparison to CAI. Similarly, under limited irrigation conditions, the maximum yield was observed with OMLI treatment (Table 2). The 1000-grain weight did not influence significantly. The increase in growth and yield attributes consequently led to increase in yield of wheat (Fig 1). In comparison to control, the per cent increase in wheat grain yield due to mulching, Pusa hydrogel and aqua-sowing under assured and limited irrigated condition was 11.4, 6.7, 5.9 and 22, 14.8, 13.2%, respectively. Similarly, the straw yield was also found 12.6, 7.9, 6.5 and 21.6, 14.7, 11.6% higher than control due to mulching, Pusa hydrogel and aqua-sowing under assured and limited irrigation conditions, respectively.

Table 2 Effect of moisture-stress management practices on growth and yield attributes of wheat (Pooled data of 3 years)

Treatment	Plant height (cm)	LAI at 90 DAS	Tillers/m ²	Spikes/plant	Grains/spike	Spike length (cm)	1000-grain weight (g)
OMAI	87.2	5.19	560	7.3	44.7	9.6	41.5
PHAI	86.4	5.12	549	7.0	42.9	9.6	41.3
ASAI	84.4	5.21	530	6.9	42.8	9.2	41.1
CAI	83.5	4.90	493	6.7	41.4	9.8	40.3
OMLI	82.3	4.91	465	6.3	39.6	8.7	40.2
PHLI	82.2	4.97	436	6.1	38.3	8.0	40.0
ASLI	82.1	4.81	434	6.0	37.9	8.6	39.9
CLI	76.7	4.54	404	5.6	35.0	8.1	39.7
SEm \pm	1.43	0.04	5.06	0.07	0.50	0.41	0.13
CD (<i>P</i> =0.05)	4.30	0.12	15.49	0.23	1.53	1.26	0.41

Treatments: Pusa hydrogel under assured irrigation (PHAI); Organic mulch under assured irrigation (OMAI); Aqua sowing under assured irrigation (ASAI); Control under assured irrigation (CAI); Pusa hydrogel under limited irrigation (PHLI); Organic mulch under limited irrigation (OMLI); Aqua sowing under limited irrigation (ASLI); Control under limited irrigation (CLI).

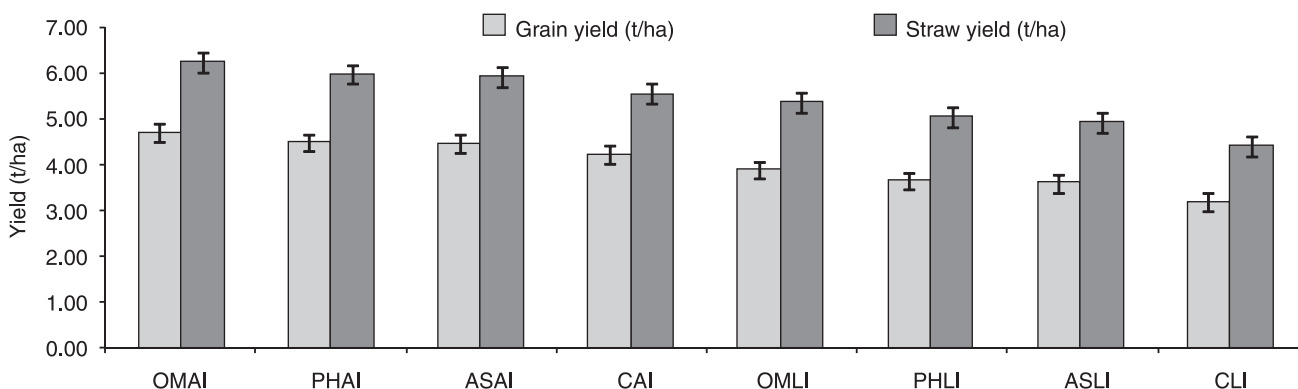


Fig 1 Effect of moisture-stress management practices on productivity of wheat (Pooled data of 3 years).

The performance of various moisture stress management techniques was better under limited irrigation condition as compared to assured irrigation condition. The organic mulching reduced evaporation losses of soil moisture which consequently improved rhizospheric moisture and nutrient availability (Acharya *et al.* 1998). The higher wheat grain and straw yield in the organic mulching treatment could be due to temperature moderation effect on wheat crop and less infestation of weeds, which provided competition free environment to wheat (Das *et al.* 2014, Bana *et al.* 2016, Bamboriya *et al.* 2017). Further, organic mulching also improves the soil moisture holding capacity, bulk density and rooting density thus provided favourable microclimate and enhanced the crop yield (Acharya *et al.* 1998). Similarly, the improved performance of Pusa hydrogel application was owing to improvement of soil hydro-physical properties such as porosity, bulk density, mean weight diameter, aggregate stability and hydraulic conductivity. The absorption of 300–400 times of weight of hydrogel in pure water and gradually release to crop enhanced seed germination and the rate of seedling emergence and further, root growth and density (Patil *et al.* 2014, Narjary and Aggarwal 2014). Pusa

hydrogel improved the plants to withstand extended moisture stress, delays onset of permanent wilting point and reduction in irrigation and fertigation requirements of crops (Bana *et al.* 2013). The aqua-sowing of wheat also facilitated quick germination and early establishment of robust seedlings and thus improved the crop yield. Better root development in initial stage enhances nutrient availability to the crop and also imparts strength to the crop plants to withstand soil moisture stress (Rana and Bana 2012, Bana *et al.* 2013).

Nutrient acquisition and soil fertility

Under assured irrigation, the maximum NPK uptake was recorded under OMAI, i.e. 97.9, 11.7 and 112.3 kg/ha, respectively during three years. It was followed by PHAI (94.8, 11.1 and 106.9 kg/ha) and ASAI (94.6, 11.0 and 105.4 kg/ha) and was statistically superior over control (Table 3, 4). Similarly, NPK uptake in limited irrigation regime remained higher in OMLI (83.9, 9.6 and 84.8 kg/ha) during three years, respectively), followed by PHLI (79.6, 9.0 and 79.7 kg/ha) and ASLI (78.7, 8.8 and 77.5 kg/ha). Application of organic-mulch, Pusa hydrogel and aqua-sowing under assured and limited irrigation condition

Table 3 Effect of moisture-stress management practices on quality and nitrogen uptake in wheat (Pooled data of 3 years)

Treatment	Protein content in grains (%)	Proline content (µg/g FW at flowering)	N uptake (kg/ha)		
			Grains	Straw	Total
OMAI	9.85	5.02	73.9	23.9	97.9
PHAI	9.94	5.90	71.4	23.4	94.8
ASAI	9.94	6.49	70.9	23.7	94.6
CAI	9.93	8.38	66.9	22.1	89.0
OMLI	10.03	9.34	62.1	21.8	83.9
PHLI	10.13	10.18	58.9	20.7	79.6
ASLI	10.17	13.08	58.3	20.4	78.7
CLI	10.33	16.22	52.4	18.8	71.2
SEm±	0.31	0.17	1.69	0.59	2.19
CD (P=0.05)	0.92	0.53	5.17	1.80	6.70

Refer Table 2 for the treatments

Table 4 Effect of various moisture-stress management practices on phosphorus and potassium uptake in wheat (Pooled data of 3 years)

Treatment	P uptake (kg/ha)			K uptake (kg/ha)		
	Grains	Straw	Total	Grains	Straw	Total
OMAI	10.52	1.14	11.67	19.2	93.1	112.3
PHAI	9.98	1.11	11.09	18.3	88.6	106.9
ASAI	9.92	1.08	11.00	18.0	87.5	105.4
CAI	9.40	1.07	10.47	16.8	77.9	94.7
OMLI	8.58	1.04	9.62	14.7	70.1	84.8
PHLI	8.06	0.89	8.95	13.8	65.9	79.7
ASLI	7.97	0.85	8.82	13.6	64.0	77.5
CLI	7.03	0.77	7.80	11.6	54.4	66.0
SEm±	0.23	0.06	0.27	0.37	2.58	2.76
CD (P=0.05)	0.70	0.17	0.82	1.13	7.80	8.36

Refer Table 2 for the treatments

increased N uptake by 10, 6.5, 6.3 and 17.8, 11.8, 10.5%, respectively, over control. Under limited irrigation the highest P uptake (9.6 kg/ha) and K uptake (84.8 kg/ha) was recorded with organic-mulch and similar trend was observed under assured irrigation treatments. The adequate supply of moisture to the plants known to have the positive influence on nutrient availability and accumulation, leading to enhance the concentration of NPK and their uptake by the crop (Tetarwal and Rana 2006). Further, nutrient uptake is the function of nutrient concentration in grain and straw and yield of grain and straw, therefore, the higher grain and straw yield in the treatments where moisture stress was less, gave enhanced nutrient uptake (Ansari *et al.* 2011).

The soil fertility status at the end of three years of crop cycle revealed that available NPK and soil organic carbon (SOC) in soil after wheat harvest significantly enhanced with application of organic-mulch under both the moisture regimes (Table 5). Application of organic-mulch enhanced available soil NPK status by 7.8, 5.8, 3.8% in assured, and 7.9, 7.2, 6.4% in limited irrigation, respectively. The other moisture-stress management practices did not influence the available nutrient status of the soil significantly. Bulk density was recorded lowest under organic-mulching followed by Pusa hydrogel, whereas it was highest under control

Table 5 Effect of moisture-stress management practices on soil conditions after 3 cycles of wheat

Treatment	Bulk density (Mg/m ³)	Soil organic carbon (%)	Available-N (kg/ha)	Available-P (kg/ha)	Available-K (kg/ha)
OMAI	1.47	0.38	198.7	14.5	244.3
PHAI	1.50	0.35	192.7	13.8	238.3
ASAI	1.51	0.35	190.8	13.7	239.0
CAI	1.53	0.34	184.3	13.7	235.3
OMLI	1.46	0.38	196.7	14.9	247.0
PHLI	1.49	0.35	190.0	14.1	239.3
ASLI	1.52	0.34	190.3	14.0	238.0
CLI	1.53	0.34	182.3	13.9	232.2
SEm±	0.006	0.005	2.08	0.14	1.83
CD(P=0.05)	0.019	0.016	6.38	0.43	5.59

Refer Table 2 for the treatments

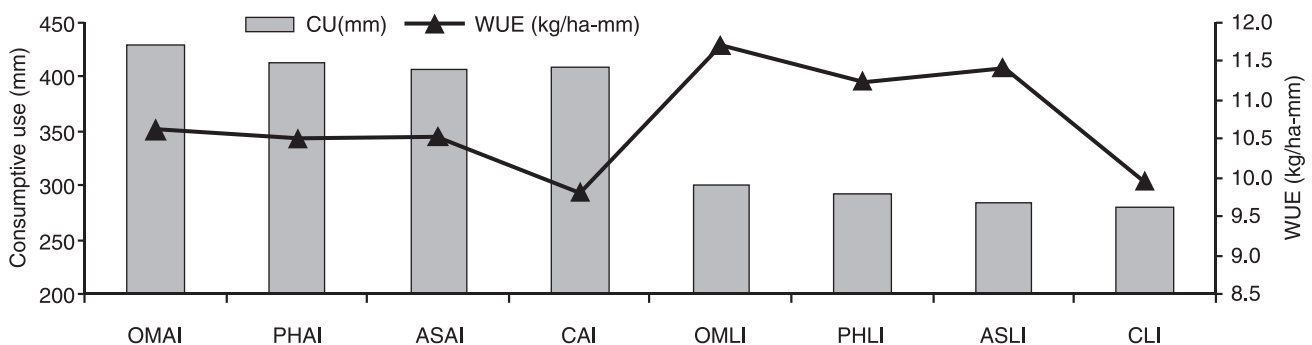


Fig. 2 Effect of moisture-stress management practices on consumptive-use and water-use-efficiency of wheat (Pooled data of 3 years).

treatment. The reason for improvement in available nutrient status in the soil may be enrichment of soil profile due to decomposition of organic mulch and increased microbial activity under the treatment. Acharya *et al.* (1998) also found the improvement in available nutrient status and physical properties of the soil due to mulching.

Protein content and proline accumulation

The highest protein content in the grains and proline concentration in the leaves at flowering stage was recorded with CLI (Table 3). The wheat crop faces maximum moisture stress in control which enhanced the proline content. Under assured irrigation supply, there was no significant variation in protein and proline concentration under different moisture management treatment as the stress under assured supply of irrigation was minimal. The increased concentration of protein and proline in wheat due to moisture stress was also reported by Kilic and Yagbasanlar (2010) and Keyvan (2010).

Water use efficiency

The use of mulching, hydrogel and aqua-sowing increased the consumptive-use (CU) and water-use efficiency (WUE) in wheat as compared to no-moisture management. The highest WUE in limited irrigation was observed with organic-mulch followed by aqua-sowing and Pusa hydrogel and the lowest was found under control. Similar trend was recorded under assured irrigation. However, the WUE under limited irrigation regimes, in general, was higher than assured irrigation conditions (Fig 2). The improvement in WUE under mulch and hydrogel was owing to reduction in severe water deficit, particularly mid day moisture stress, led to maintenance of optimum leaf water potential and improvement in crop yield. The close correlation was observed in WUE and proline accumulation (Fig 3). The linear equation of $Y = 1.504X + 2.555$ was obtained with $R^2 = 0.93$ shows that a high positive correlation existed in WUE and proline content. Further, due to reduction in evapotranspiration losses of soil moisture was also avoided under moisture conservation practice. Since, the WUE is the function of yield and evapotranspiration, therefore, the twin benefits of reduced moisture loss and improved crop yield through moisture management practices improved the WUE (Zhang *et al.* 1998, Bana *et al.* 2016). Pearson's correlation matrix analysis evaluated for yield, nutrient

Table 6 Pearson correlation matrix of different characters of wheat as influenced by moisture-stress management practices

Character	Grain yield (t/ha)	Straw yield (t/ha)	Proline content (µg/g)	WUE (kg/ha-mm)	Total N uptake (kg/ha)	Total P uptake (kg/ha)	Total K uptake (kg/ha)
Grain yield (t/ha)	1.00	0.99**	-0.97**	-0.20 ^{NS}	0.99**	0.99**	0.99**
Straw yield (t/ha)	0.99**	1.00	-0.98**	-0.11 ^{NS}	0.99**	0.99**	0.99**
Proline content (µg/g)	-0.97**	-0.98**	1.00	0.05 ^{NS}	-0.97**	-0.96**	-0.96**
WUE (kg/ha-mm)	-0.20 ^{NS}	-0.11 ^{NS}	0.05 ^{NS}	1.00	-0.18 ^{NS}	-0.21 ^{NS}	-0.21 ^{NS}
Total N uptake (kg/ha)	0.99**	0.99**	-0.97**	-0.18 ^{NS}	1.00	0.99**	0.99**
Total P uptake (kg/ha)	0.99**	0.99**	-0.96**	-0.21 ^{NS}	0.99**	1.00	0.99**
Total K uptake (kg/ha)	0.99**	0.99**	-0.96**	-0.20 ^{NS}	0.99**	0.99**	1.00

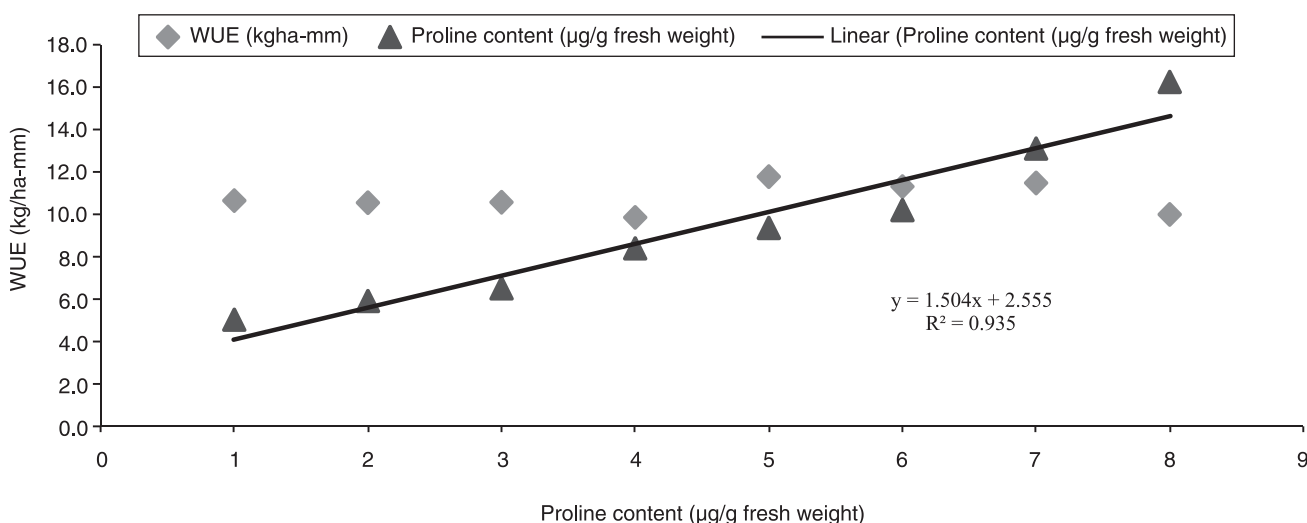


Fig 3 Relationship between water-use efficiency and proline content in wheat.

uptake and WUE parameters indicated that the grain yield ($r = 0.97$, $P = 0.05$) and straw yield ($r = 0.98$, $P = 0.05$) are negatively correlated with proline content (Table 6). The correlation of WUE with almost all the parameters remained non-significant ($P = 0.05$). Similarly, N, P and K uptake remained positively correlated with grain and straw yield but were negatively correlated with proline content and WUE. Similar results were also reported by Kilic and Yagbasanlar (2010) in durum wheat.

Conclusions

This study highlighted that under limited irrigation availability, organic-mulching can be a good option to achieve higher crop and water-use efficiency and nutrient uptake and reduce the moisture-stress in semi-arid ecologies of north-western Indo-Gangetic plains. Organic mulching was followed by Pusa hydrogel and aqua-sowing with respect to above parameters with more pronounced effects under limited irrigation regimes. Overall, the soil moisture management technologies like organic mulch, Pusa hydrogel and aqua-sowing impart greater significance for sustainable wheat production under water starved agro-ecosystems.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support

and guidance of Dr Anupama Singh, Head, Division of Agricultural Chemicals, IARI, New Delhi for the present research. The assistance received from the Division of Agronomy and Division of Plant Physiology, ICAR–Indian Agricultural Research Institute (IARI), New Delhi is gratefully acknowledged.

REFERENCES

Acharya C L, Kapoor O C, and Dixit S P. 1998. Moisture conservation for rainfed wheat production with alternative mulches and conservation tillage in the hills of north-west India. *Soil and Tillage Research* **46**: 153–63.

Ansari M A, Rana K S, Rana D S and Kumar P. 2011. Effect of nutrient management and anti-transpirant on rainfed sole and intercropped pearl millet and pigeonpea. *Indian Journal of Agronomy* **56**(3): 209–16.

Bamboriya S D, Bana R S, Pooniya V, Rana K S and Singh Y V. 2017. Planting density and nitrogen management effects on productivity, quality and water-use efficiency of rainfed pearl millet (*Pennisetum glaucum*) under conservation agriculture. *Indian Journal of Agronomy* **62**(3): 363–6.

Bana R S, Pooniya V, Choudhary A K, Rana K S and Tyagi V K. 2016. Influence of organic nutrient sources and moisture management on productivity, bio-fortification and soil health in pearl millet (*Pennisetum glaucum*) + clusterbean (*Cyamopsis tetragonaloba*) intercropping system of semi-arid India. *Indian Journal of Agricultural Sciences* **86**(11): 1418–25.

Bana R S, Rana K S, Dass A, Choudhary A K, Pooniya V, Vyas A

- K, Kaur R, Sepat S and Rana D S. 2013. *A Manual on Dryland Farming and Watershed Management*, p 104. IARI, New Delhi.
- Bouyoucos G J. 1962. Hydrometer method for making particle size analysis of soils. *Agronomy Journal* **54**: 464.
- Chattaraji S, Chakraborty D, Garg R N, Singh R, Singh G P, Sehgal V K, Sahoo R N, Singh S, Gupta V K and Chand D. 2011. Evaluating the effect of irrigation on crop evapotranspiration in by combining conventional and remote sensing methods. *Journal of Agricultural Physics* **11**: 35–52.
- Choudhary A K, Singh A and Yadav D S. 2010. 'On Farm Testing' of wheat cultivars for site-specific assessment under varied bio-physical regimes in mid-hill conditions of Mandi district of Himachal Pradesh. *Journal of Community Mobilization and Sustainable Development* **5**(1): 1–6.
- Choudhary A K, Thakur R C and Kumar N. 2008. Effect of integrated nutrient management on soil physical and hydraulic properties in rice-wheat crop sequence in north-western Himalayas. *Indian Journal of Soil Conservation* **36**(2): 97–104.
- Das T K, Bhattacharyya R, Sudhishri S, Sharma A R, Saharawat Y S, Bandyopadhyay K K, Sepat S, Bana R S, Aggarwal P, Sharma R K, Bhatia A, Singh G, Datta S P, Kar A, Singh B, Singh P, Pathak H, Vyas A K, Jat M L. 2014. Conservation agriculture in an irrigated cotton–wheat system of the western Indo-Gangetic Plains: Crop and water productivity and economic profitability. *Field Crop Research* **158**: 24–33.
- El-Hady O A and Abo-Sedera S A. 2006. Conditioning effect of composts and acrylamide hydrogels on a sandy calcareous soil. II-physico-bio-chemical properties of the soil. *International Journal of Agriculture and Biology* **8**: 876–84.
- Irigoyen J J, Emerich D W and Sanchez-Diaz M. 1992. Water stress induced changes in concentrations of proline and total soluble sugars in modulated alfalfa (*Medicago sativa*) plants. *Plant Physiology* **84**(1): 55–60.
- Jackson M L. 1973. *Soil Chemical Analysis*, 2nd Edition, pp 498. Prentice Hall of India Pvt Ltd, New Delhi.
- Keyvan S. 2010. The effects of drought stress on yield, relative water content, proline, soluble carbohydrates and chlorophyll of bread wheat cultivars. *Journal of Animal and Plant Sciences* **8**(3): 1051–60.
- Kilic H and Yagbasanlar T. 2010. The effect of drought stress on grain yield, yield components and some quality traits of durum wheat cultivars. *Notulae Botanicae Horti Agrobotanici Cluj-Napoca* **38**(1): 164–70.
- Kumar A, Rana K S, Rana D S, Bana R S, Choudhary A K, and Pooniya V. 2015. Effect of nutrient and moisture management practices on crop productivity, water-use efficiency and energy dynamics in rainfed maize (*Zea mays* L.) + soybean (*Glycine max* L.) intercropping system. *Indian Journal of Agronomy* **60**(1): 152–56.
- MoA&FW. 2016–17. Annual Report 2016–17, Department of Agriculture, Cooperation and Farmers' Welfare, Ministry of Agriculture and Farmers Welfare, New Delhi, p 188.
- Narjary B and Aggarwal P. 2014. Evaluation of soil physical quality under amendments and hydrogel applications in a soybean-wheat cropping system. *Communications in Soil Science and Plant Analysis*. DOI: 10.1080/00103624.2013.875191.
- Olsen B C, Cole C V, Watenabe F S and Dean L A. 1954. Estimation of available phosphorus by extraction with sodium carbonate. USDA Circular No. 939, p 19.
- Patil M D, Dhindwal A S and Rajanna G A. 2014. Integrated moisture stress management in wheat (*Triticum aestivum*). *Indian Journal of Agronomy* **59**(4): 629–33.
- Piper C S. 1950. *Soil and Plant Analysis*, p 286-7. The University of Adelaide, Australia.
- Rana K S and Bana R S. 2012. Studies on aqua-fertilization with and without nitrogen in wheat (*Triticum aestivum*) under rainfed conditions. *Research on Crops* **13**(2): 453–5.
- Rana K S and Singh R K. 2006. Nutrient management using aqua-fertilization in wheat under dryland condition. *Crop Research* **32**(3): 300–1.
- Rana K S, Choudhary A K, Sepat S, Bana R S and Das A. 2014. *Methodological and Analytical Agronomy*, p 276. Post Graduate School, IARI, New Delhi, India.
- Richards L A. 1954. *Diagnosis and Improvement in Saline, Alkali Soils*. Handbook No. 60, USDA, Washington.
- Sheoran O P, Tonk D S, Kaushik L S, Hasija R C and Pannu R S. 1998. Statistical software package for agricultural research workers. (In) *Recent Advances in information theory, Statistics & Computer Applications*, pp 139–43. Hooda D S and Hasija R C (Eds). Department of Mathematics and Statistics, CCS HAU, Hisar.
- Shinde S S. 2011. 'Studies on some physiological traits in wheat under water stress condition'. Ph D thesis, University of Pune. URL: <http://hdl.handle.net/10603/3267>.
- Singh R K, Singh S and Singh A K. 2005. Effect of aqua-ferti sowing and graded nitrogen on productivity, nutrient uptake and moisture use by wheat under rainfed conditions. (In) *Abstract National Symposium on Efficient Water Management for Eco-friendly Sustainable and Profitable Agriculture*, IARI, New Delhi, p 174–5.
- Subbiah B V and Asija G L. 1956. A rapid procedure for the estimation of available N in soils. *Current Science* **25**(8): 259–60.
- Taban M and Naeini S A R M. 2006. Effect of aquasorb and organic compost amendments on soil water retention and evaporation with different evaporation potentials and soil textures. *Communications in Soil Science and Plant Analysis* **37**: 2031–55.
- Tetarwal J P and Rana K S. 2006. Impact of cropping system, fertility status and moisture conservation practices on productivity, nutrient uptake, water use and profitability of pearl millet under rainfed conditions. *Indian Journal of Agronomy* **51**(4): 263–6.
- Walkley A J and Black C A. 1934. Estimation of soil organic carbon by the chronic acid titration method. *Soil Science* **37**: 29–38.
- Zhang J, Sui X, Bin Li, Baolin Su, Jianmin Li and Zhou D. 1998. An improved water-use efficiency for winter wheat grown under reduced irrigation. *Field Crops Research* **59**: 79–98.