



Effect of Agronomic Intervention on the Productivity of *Khadin* Cultivated Rabi Crops in Arid Region for Enhancing Farm Income: A Case Study from Jodhpur (Rajasthan, India)

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Abstract: *Khadin* is a traditional runoff farming system practiced in the Indian Thar Desert, designed to facilitate cultivation of at least one crop annually in regions receiving approximately 200 mm of annual rainfall. Strategic selection of high-value crops and use of collected rainwater for supplemental irrigation are considered vital for enhancing farm income and water productivity (WP) in *khadin* systems. The present study aimed to: (i) develop a facility for providing supplementary irrigation to test crops using solar energy; (ii) identify most remunerative crop under prevailing *khadin* conditions; (iii) determine optimal irrigation levels for maximizing water productivity; and (iv) validate research findings through measurements of soil-water content and crop physiological characteristics. A water storage structure with a capacity of 3.2 million liters was constructed within the *khadin* for surplus runoff collection and lined with 300-micron HDPE sheet to enable supplementary irrigation. Experiments were conducted with three crops-mustard (*B. juncea*), barley (*H. vulgare*), and gram (*C. arietinum*)-under three levels of supplementary irrigation to identify the most profitable crop. Standard methodologies were employed to assess soil-water content and crop physiological responses. Results revealed that gram with supplemented irrigation produced the highest gram equivalent yield (GEY) of 2047 kg ha⁻¹, which was 32% and 20% higher than barley and mustard, respectively. The highest economic water productivity (EWP) of Rs. 122.54 m⁻³ was recorded for gram, representing an Rs. 31.65 m⁻³ advantage over barley. Additionally, a single supplementary irrigation increased gram grain yield by 479 kg ha⁻¹ and farm income by Rs. 28,740 ha⁻¹ compared to farmer-managed gram cultivation. Enhancing existing *khadin* systems with supplementary irrigation at critical crop growth stages and selecting suitable crops can significantly improve productivity and farm profitability in semi-arid and arid regions of India.

Key words: Chlorophyll, deficit irrigation, *khadin*, water productivity, yield.

For the past three to four decades, water scarcity has been a widely discussed issue, with many regions around the world affected by its shortage (Mancosa *et al.*, 2015). Water is the primary limiting factor for agricultural production in the western desert districts of Rajasthan, where the rainfall gradient varies from 500 mm in the eastern parts to 100 mm near the western international borders. Under such conditions conventional rainfed cropping is highly uncertain. For ensuring at least one crop in year, the Paliwal farming community of the Jaisalmer district had evolved a unique runoff farming system called “*khadin*” in the Indian Thar desert in 15th century (The Rajputana Gazetteer, 1879; Mishra, 1994). The prevailing *khadin* system of Indian Thar desert resembled very much to ‘Liman’ (Gr. Limne-March, Pond) system of rain water harvesting for agriculture as described by Bruins *et al.*, 1986 in which Liman (Israel name for an artificial earthen bund) is constructed to collect floodwater by damming a desert wadi (Arabic word meaning valley). The size of ‘liman’ is generally larger in *khadin* cultivation than in the other systems of runoff farming (Prasad *et al.*, 2004).

Khadin system is essentially a runoff based agricultural system on the principles of rainwater harvesting from a rocky/gravelly catchment; diverting and collecting the runoff right on the farm land by making an earthen embankment, inundating the land during rainy season (Mishra, 1993). After recession of accumulated water, *khadins* are cultivated to grow kharif (July-October) or rabi (November-March) season crops depending upon depth of impounded water. The components (Fig. 1) for the success of these system in drier areas consisted of (i) an upland rocky or gravelly catchment that generates sufficient runoff, (ii) an earthen or gravel bund strong enough to hold collected runoff in the *khadin* bed, (iii) a low lying farm bed/*khadin* bed in the vicinity of catchment in which runoff water remained ponded for a period of 2 to 3 months and crops are grown on this area after recession of ponded water, (iv) water regulating structures such as sluice or spillways that ensures level of water ponding and water discharge to low lying interconnected *khadins*, (v) a dug well that help in ground recharge and also serve the purpose of drinking water and (vi) seepage

area through which surplus rainwater from the upland *khadin* passes to interconnected chain of low lying *khadins* (Singh and Kolarkar, 1983; Tewari, 1988). The size of catchment to *khadin* bed (*khadin* farm) varied in the desert areas depending upon the rainfall, slope and topography. Assuming 60% probability of annual rainfall, the ratio between cultivated and catchment area varies from 1:15 to 1:56 (Narain *et al.*, 2005). Prasad *et al.*, 2004 reported a minimum ratio of at least 15:1 for efficient agriculture in the Jaisalmer (India) conditions receiving annual rainfall around 150 mm. For Jodhpur (India), the estimated ratio for annual rainfall zone of 380 mm is 12:1 in which catchment area of 164.11 ha generated runoff for the 5 *Khadin* farms each having size of 2.5 ha. In general, most of the traditional *khadins* are constructed in such a way that the runoff generated from rainfall of 75 to 100 mm is sufficient to charge the soil with sufficient moisture (Bandyopadhyay *et al.*, 2020). The size of *khadins* can vary from few to hundreds of hectares and their ownership and management may be communal or individual. The biggest *Khadin* of 300 ha (Masurdi-*khadin*) is found in the Masurdi village of Jaisalmer (India) and is 400 years old community *khadin* owned/shared by the farmers of more than 10 villages (Chatterji and Kar, 1992).

Khadins are considered low input high output man-made production systems that have greater socio-economic and ecological impacts in the desert areas. *Khadin* lands provide two- to three-fold increase in crop production as compared to normal agricultural lands (CSR Portal 2018). A study conducted by CAZRI, showed that about 2.5 to 3.0 t ha⁻¹ wheat and 1.5 to 2.5 t ha⁻¹ gram yields could be achieved successfully in *khadins* without use of chemical fertilizers (Kolarkar, 1990). The *khadins* at Bawarli-Bambore in Jodhpur generated an income of Rs. 18,500 ha⁻¹ through food production during the extreme drought of 2002 (CAZRI, 2007). *Khadin* farmers are economically more secure compared to non-*Khadin* farmers, due to the presence of more productive animals and earnings from farm produce in the form of grains and fodder (Kolarkar and Bharara, 1988). Apart from providing agricultural yields and providing financial security to locals, *khadins* make positive environmental contributions. The planting of woody perennials

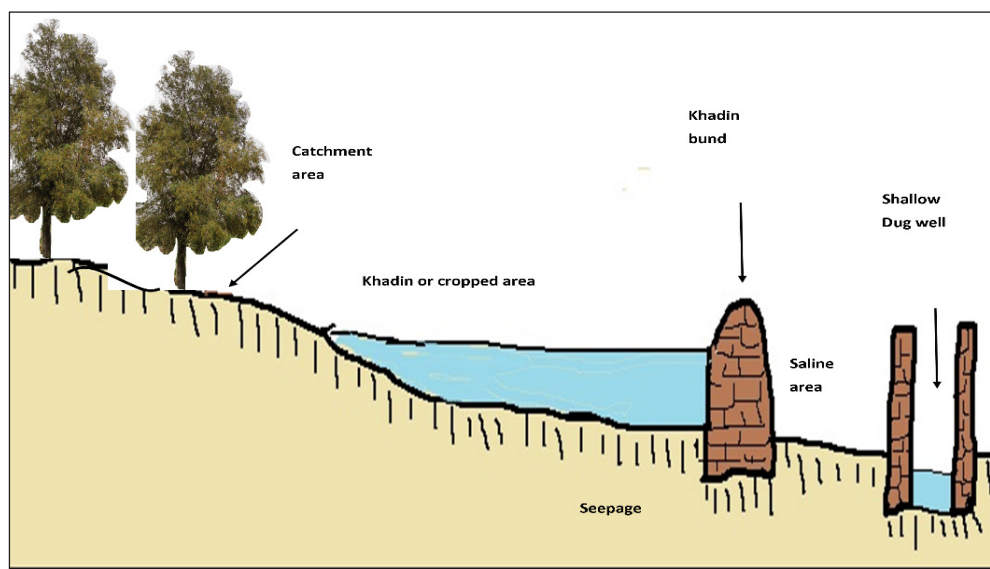


Fig. 1. Khadin water harvesting system.

and horticultural plants on the *khadin* bunds served both productive and protective roles. Besides, about 62% of *khadin* water contributes to groundwater recharge (Khan and Narain, 2003) and facilitates vegetation growth around the site. Another ecological impact of *khadins* is their effectiveness in preventing soil erosion by increasing vegetation cover (Agarwal and Narain, 1997).

Khadin soils are more fertile and their water holding capacity often ranges from 200-250 mm m^{-1} depth and differ significantly from the ordinary desert soils around (Chatterji and Kar, 1992). The texture of *khadin* bed is different than the catchment and upper and middle beds of the *khadin*. The clay content was reported to increase from 10.72% in upper catchment to 23.24% in the *khadin* bed (CAZRI, 2003). Similarly, silt content increased from 10 to 20% in *khadin* beds than catchment area. The electrical conductivity ($dS m^{-1}$), pH, organic carbon content (%) for older *khadin* was 0.40, 7.89 and 0.26. The values of available P and K were 57.52 and 208.30 $kg ha^{-1}$. The increased content of silt helped in prevention of seepage losses of conserved rainwater into deeper soil layers beyond crop root zone and enhanced water holding capacity of *khadin* soils from 7.92 to 13.88% (CAZRI, 2003).

The salinity buildup in *khadins* is lower than the vicinity area and catchment owing to leaching (Goyal *et al.*, 2018) and intermittent flushing of salts from the *khadin* area. Role of bunds has been considered very important

in regulating the salinity level. The sideways movement of water into the large bunds pushes most of the salts in bunds which accumulate the maximum quantity of salts (Kolarkar *et al.*, 1983). In another way dissolved salts in inundated water goes as overflow and passes through spillways during flash floods caused by heavy rainfall events or in some *khadins* shallow dug seepage wells helps in removal of salts from inside *khadin* bed due to acceleration of seepage in wells outside bunds because of continuous removal of water for livestock drinking.

The moisture level remains significant even 3 to 4 months after the runoff is drained from the *khadins*. A gentle slope of 2 to 5% from pediment catchments to most of the *khadin* beds is reported in western Rajasthan (Khan, 2005) that create an altitudinal difference of 35 m to 40 m between these two land forms through a length of 2 to 3 km and a continuous flow of soil moisture from upland catchment to *khadin* farms maintained during the entire rabi crop season. Besides, higher content of alluvial silt in *khadin* beds supported in maintaining higher water holding capacity and slow down infiltration rate beyond crop rhizosphere during entire growing season (Goyal *et al.*, 2018).

In western part of Rajasthan, the coefficient of variability in rainfall is 40% in the east which increases to 70% in western part of Jaisalmer district (Narain and Singh, 2002). Thus, in some years insufficient runoff is generated to support scheduled cropping on the conserved moisture

and in some years, there is surplus. On some occasions 25 to 40% higher runoff generation was reported with rainfall intensity of more than 50 mm (Khan and Narain, 2003). The excess water gets wasted without any beneficial use from the *khadin* farms. Old *khadins* have been provided with the provision of spillway and sluice to regulate water impoundment. However, in most of the newly constructed *khadins*, spillways have not been provided to allow flow of excess water to avoid damage of the *khadin* bunds (Prasad *et al.*, 2004). During grain filling stage, insufficient availability of soil moisture together with higher air temperature (around 37°C) causes forced maturity of the crops and farmers get lower yields in the absence of provision of supplementary irrigation source from *khadins*. Hence, provision should be made in the *khadin* design for storing surplus water in a leak-proof runoff storage structure, the water of which can be utilized for supplementary irrigation during terminal water stress or water can be used for increasing area under irrigation for growing of crops during rabi and additional crops mainly fodder during late winter. The selection of crops based on the availability of soil moisture in the rhizosphere is the first step in realizing the economic and efficient use of conserved moisture but most of the farmers tend to make risk-averse choices of crop and farm inputs. Hence, present study was undertaken to identify more remunerative crop in term of water productivity, yield and farm income under provision of supplementary irrigation from collected runoff in the *khadin* systems of Rajasthan.

Materials and Methods

Study site

The study was conducted in the heart of the arid zone of Rajasthan, located at 26°21'N latitude and 73°42'E longitude and with altitude at 196 m above mean sea level. The project site village Ajeet Nagar is one of the villages of Gram Panchayat Bawarli located in Balesar Tehsil of Jodhpur district in Rajasthan. This site was chosen based on its representative characteristics for arid areas in the region to assure that project efforts are scalable as well as their demographic characteristics which are also representative of the region. As per available land use data, the total geographical area of the village is 818.90 ha of which 649.33

ha is net sown area, 164.11 ha is rocky grazing land and 5.46 ha under habitation. A sum of 1,044 people lives in 186 households in the village. There are 498 female individuals and 546 male individuals in the village. The community predominantly reared cattle and goats that grazed on the community pastures. *Dactyloctenium indicum* with sprinkling of *Acacia tortilis* forms the dominant landscape of the grazing area.

Climate of study site

The study site represents hot arid which is characterized by low rainfall (<450 mm yr⁻¹), high temperature (40-47°C) and high wind velocity (20-40 km h⁻¹). The rainfall is largely monsoon driven which comes between June and September, and accounts for about 95% of the total rainfall with high coefficient of variation (40-60%) and erratic distribution (Modgal, 2016). Moisture index in arid western Rajasthan varies from 69 to 91 and aridity index ranges between 68 and 78. Evaporation from water surface varies between 6.22 mm and 13.7 mm per day during winter and summer months, respectively. Temperature varies from below 5°C in winter to 45°C in summer. The monsoonal rainfall of 110 mm and 213 mm was received during 2019 and 2020 at the study site.

Construction of water storage structures

As per the study need, one water storage structure was constructed within *khadin* to store surplus runoff. The capacity of water storage structure was 3.2 million liters having trapezoidal shape and measuring 30 m × 30 m in top, 20 m × 20 m in bottom, height 5.06 m and slope 7.11 m (Fig. 2). Heavy machinery was used for the digging of structure of the desired dimension. This constructed water storage structure was lined with 300 micron HDPE sheet to prevent seepage losses of harvested water. The *khadin* storage structure was filled with the runoff generated from 164 ha community catchment land. Each structure was provided a sedimentation structure of 2 m × 1 m to prevent the ponds from silting and an outlet drain pipe at the opposite end for removal of excess runoff to low lying land.

Earthworks for *Khadin* improvement

Earlier the earthen embankment was repaired regularly to hold sufficient runoff.

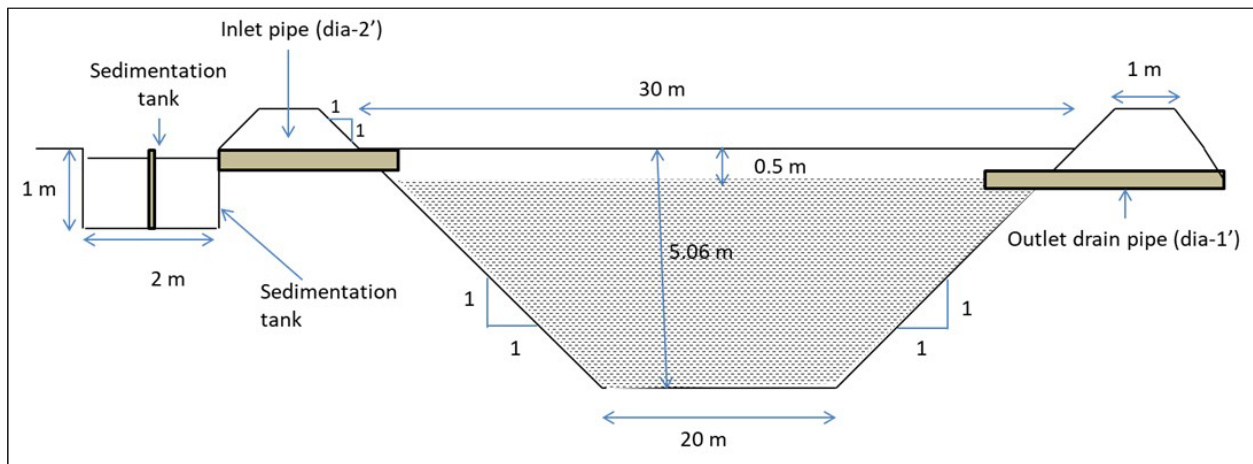


Fig. 2. Design of dugout pond for storage of 3.2 million liters rain water.

Old *khadins* have been provided with the provision of spillway and sluice to regulate water impoundment. However, in most of the newly constructed *khadins*, spillways have not been provided to allow flow of surplus runoff to avoid damage of the *khadin* bunds. In the present study a concrete-cement spillway was constructed at the low lying *khadin* bund to allow surplus runoff to interconnected other low lying *khadins* and also to prevent the damage to *khadin* bund (Fig. 3). The design takes care of the amount of runoff generated in the events of rainfall of more than 50 mm h⁻¹ and passes through the spillway safely.

Development of solar-powered pressurized irrigation system

The *khadins* are remotely located from the village habitation and in general *khadin* fields are not electrified. The problem of power source for supplementary irrigation to *khadin* crops was overcome by installing solar photovoltaic-based system. A 2 HP solar AC pump supported by 2400 Wp PV module was installed. Similarly, a pressurized irrigation system comprising mini-sprinklers system for irrigating 0.50 ha was developed for judicious use of collected rainwater.

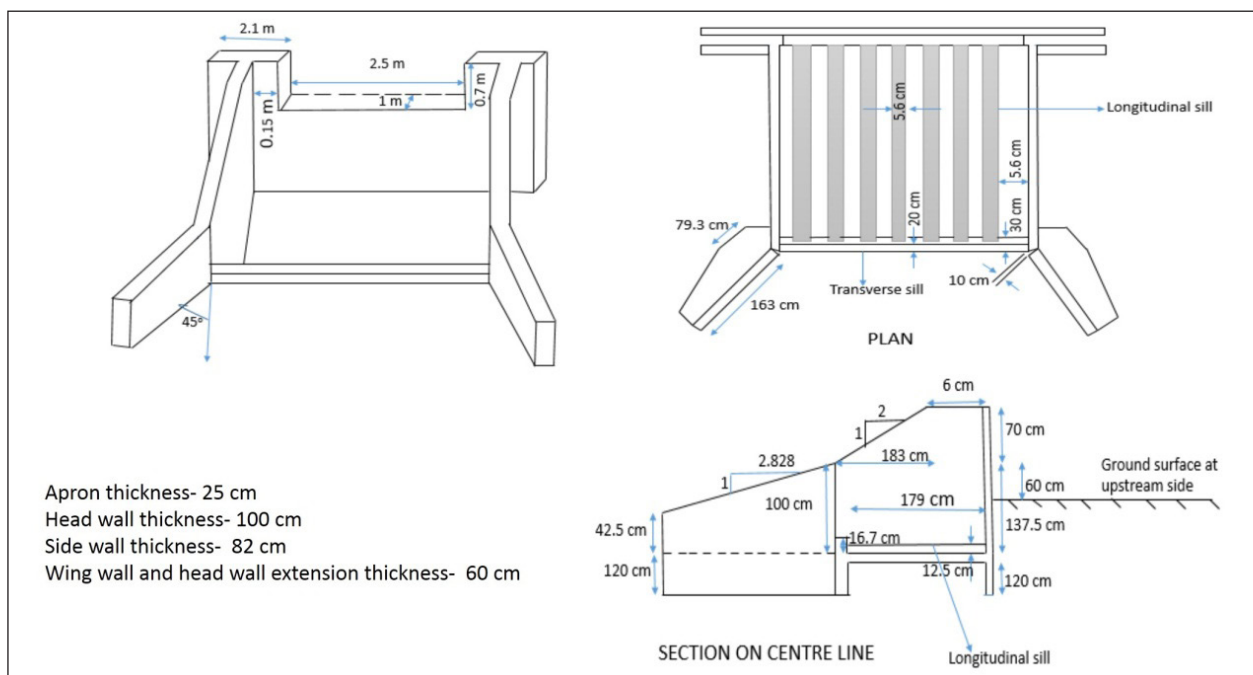


Fig. 3. A sketch of drop spillway design.

Field Experimentation

An experiment was conducted in factorial randomized block design with three replications during 2019-20 to 2020-21 in the *khadin* with three crops; mustard (*Brassica juncea*), barley (*Hordeum vulgare*) and gram (*Cicer arietinum*) on conserved soil moisture to ascertain the most suitable crop in the available conserved water and supplemented with 50% (70 mm), 25% (105 mm) and control (no-deficit) levels of irrigation as second factor. One pre-sowing irrigation from the harvested surface water of 35mm was given to all the crops at the time of sowing in the first week of November using mini-sprinklers having discharge of 7.2 mm hr⁻¹ and this irrigation was included in the calculation of the total irrigations applied to each crop. The sprinklers were operated using 2400 Wp solar panel connected through 2 HP solar AC pump. The shallow soils of the experiment field (depth <60 cm) were sandy loam having pH 8.68-8.70, EC 0.118-0.132 dS m⁻¹, OC 0.14-0.16%, available P 8.18-9.07 kg ha⁻¹, available K 120.37-133.87 kg ha⁻¹, available S 5.87-6.49 kg ha⁻¹ and available N 105-111 kg ha⁻¹. The whole experimental field of 0.51 ha (90 m × 57 m) was divided into three equal parts for three crops and irrigation treatments were imposed on all the crops sown at same time. After accounting pre-sowing irrigation, 50%-deficit treatment was given only one irrigation of 35 mm at 25 days of crop growth coinciding the most critical growth stage of barley of crown root initiation (CRI), 25%-deficit treatment was given two irrigation each of 35 mm at CRI and 50 days of crop growth coinciding with booting stage (BS) of barley and control treatment was given three irrigations each of 35 at CRI, BS and 70 days of crop growth coinciding with grain filling (GF) stage of barley in all the three crops grown on conserved soil moisture.

Soil moisture and physico-biochemical observations were taken at 60 and 90 days of crop growth stage. The soil samples from the rhizosphere of all the three crops were taken at the time of boot (60 DAS) and dough (90 DAS) stages which coincided with the sampling of physiological parameters study from the fresh leaves. Samples were taken with the help of augur and immediately transferred in to the moisture sampling boxes. The weight of samples along with soil recorded and then dried in oven at 100°C. The dry soil samples

plus boxes weight were taken and moisture content of the 0-30 soil layer was recorded. Soil moisture from 30cm soil depth was estimated gravimetrically. For physico-biochemical study at respective stages, fully opened leaves (emerging from the whorl) were collected from a plant in each plot and were washed in tap water followed by 0.1 N HCl and distilled water. For estimation of chlorophyll 100 mg leaf samples were cut into pieces and soaked with 10 ml DMSO in a vial for 24 hours and readings were taken at respective wavelengths using UV-VIS spectrophotometer. The physico-biochemical parameters such as chlorophyll content (Hiscox and Israelstam, 1979; Arnon, 1949, Lichtenthaler and Wellburn, 1983) and to determine the relative water content (RWC), leaves were collected, immediately weighed (fresh wt.), rehydrated for 4 h (turgid wt.) and subsequently oven-dried at 85C to constant mass (dry wt.) (Weatherley, 1950) from fresh leaves were analyzed following the formulae given below.

$$\text{Chlorophyll 'a' content (mg g}^{-1}\text{)} = \frac{12.7 A_{663} - 2.69 A_{645}}{a \times 1000 \times w} \times v$$

$$\text{Chlorophyll 'b' content (mg g}^{-1}\text{)} = \frac{22.9 A_{645} - 4.68 A_{663}}{a \times 1000 \times w} \times v$$

$$\text{Total chlorophyll content (mg g}^{-1}\text{)} = \frac{20.2 A_{645} + 28.02 A_{663}}{a \times 1000 \times w} \times v$$

where, a = Length of light path in cell (usually 1 cm), w = Fresh weight of the leaf samples (g), v = Volume of extract (ml)

$$\text{RWC} = 100 \times \left(\frac{\text{fresh weight} - \text{dry weight}}{\text{turgid weight} - \text{dry weight}} \right)$$

Similarly at harvest, various yield and yield attributes were also recorded from the crops grown with field experiment as well as from farmer-grown gram crop. The yields of different crops were converted into equivalent yield of gram based on price of the produce to make comparison based on the gross or net economic returns. The gram equivalent yield (GEY) in kg ha⁻¹ was calculated by the formula as described by Verma and Modgel, 1983.

$$\text{GEY (kg ha}^{-1}\text{)} = \frac{\text{grain yield of crop (kg ha}^{-1}\text{)} \times \text{unit price of grain plus straw of crops (Rs. kg}^{-1}\text{)}}{\text{unit price of grain plus straw of gram (Rs. kg}^{-1}\text{)}}$$

The water productivity (WP) and economic water productivity (ECP) in the study was calculated following the formula given below.

$$\text{WP (kg m}^{-3}\text{)} = \frac{\text{grain yield kg}^{-\text{ha}}}{\text{water consumed (m}^3\text{)}}$$

$$EWP (Rs m^{-3}) = \frac{\text{Gross return from grain plus straw } Rs^{-ha}}{\text{water consumed } (m^3 ha^{-1})}$$

The denominator water consumed was calculated following the formula advocated by Molden (1997).

$$\text{Water consumed } (m^3 ha^{-1}) = \text{Rain} + \text{SI} + \text{GWI} + \text{net capillary rise} + \text{runon} - \text{runoff} - \text{deep percolation}$$

where, SI = surface irrigation supply from harvested rain water, GWI = groundwater irrigation supply from ground water table

In the rainfed agriculture and where ground water table is more than 75 m, the values of run-on (incoming overland flows), no capillary rise from high water table, and the values of these components are considered zero and only amount of water applied through respective treatment was considered for calculation of water consumption in the study. Volumetric soil water content was obtained by multiplying gravimetric water content by the corresponding bulk density and thickness of respective soil layers.

Statistical analysis

The statistical software OPSTAT (<http://14.139.232.166/opstat/>) was used for

analysis of data. All observed mean data of two years were subjected to analysis, and the critical differences were calculated to assess the significance of treatment means, wherever, the 'F'-test was found significant at five per cent level of significance.

Results

Physiological study of crops

The results of various physiological parameters recorded with the field experiment crops mustard, barley and gram grown in *khadin* with three levels of irrigations during rabi 2019-20-2020-21 are presented in figures 4-6. Total chlorophyll content in fresh leaves was recorded 36 and 61% higher with barley over mustard at 60 and 90 days after sowing (DAS). However, non-significance difference was recorded between barley and gram for total chlorophyll at 90 DAS. The chlorophyll content with 25% deficit and no-deficit levels of irrigation was recorded at par at 60 DAS while at 90 DAS, 50%-deficit and 25%-deficit levels recorded at par total chlorophyll. Among crops, gram recorded significantly higher ratio of chlorophyll "a" to "b" over barley

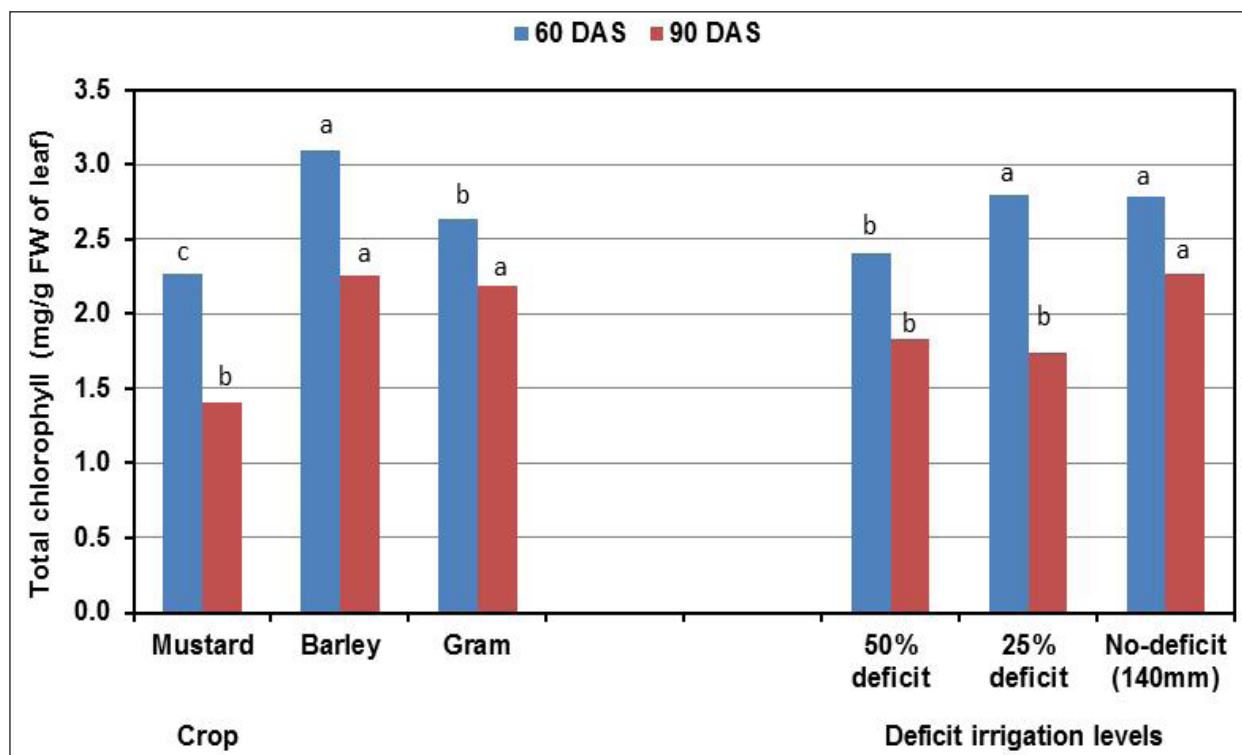


Fig. 4. Total chlorophyll content in the leaves of rabi crops received deficit irrigation levels during different growth stages (average of two years) (values within a column for each variable followed by different letter are significantly different at $P < 0.05$).

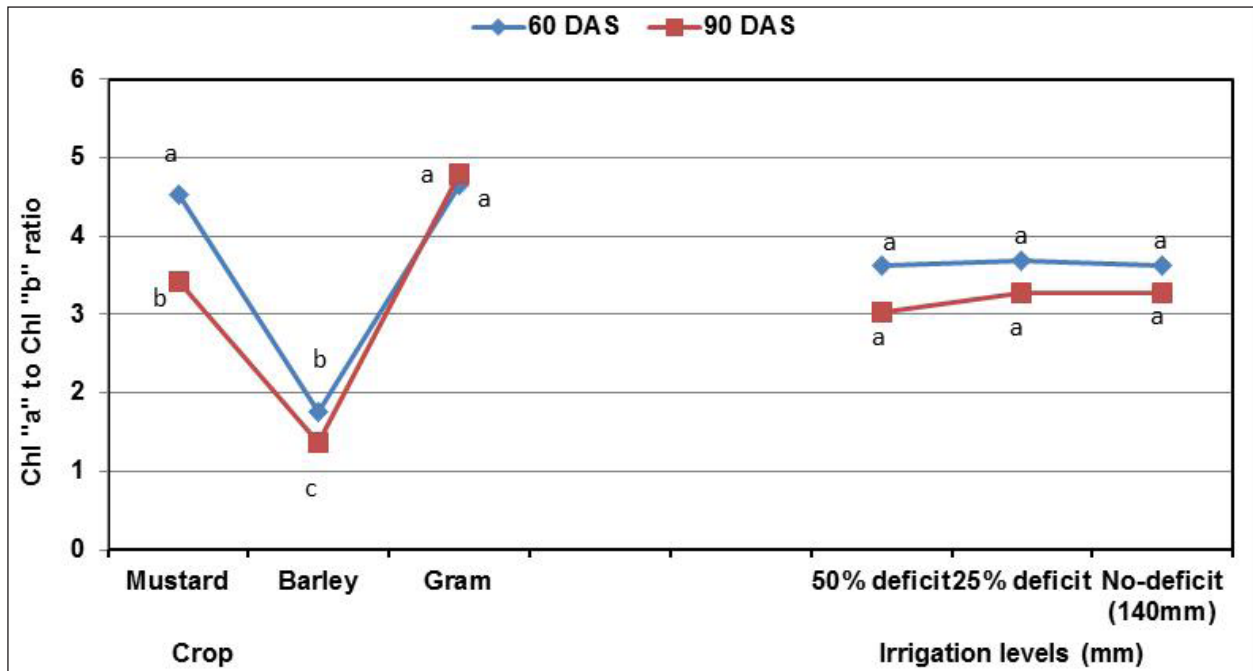


Fig. 5. Ratio of Chlorophyll "a" to Chlorophyll "b" in the leaves of rabi crops received deficit irrigation levels during different growth stages (average of two years) (values within a column for each variable followed by different letter are significantly different at $P < 0.05$).

and mustard indicating that gram is more tolerant to stresses over mustard and barley. Ratio of chlorophyll "a" to "b" did not vary with levels of irrigations at both crop growth stages. This is mainly attributed to the mean

effects of all the crops on the ratio of both the pigments. Relative water content (RWC), an indirect measurement of leaf water potential, was recorded significantly higher with mustard followed by barley and least with gram both

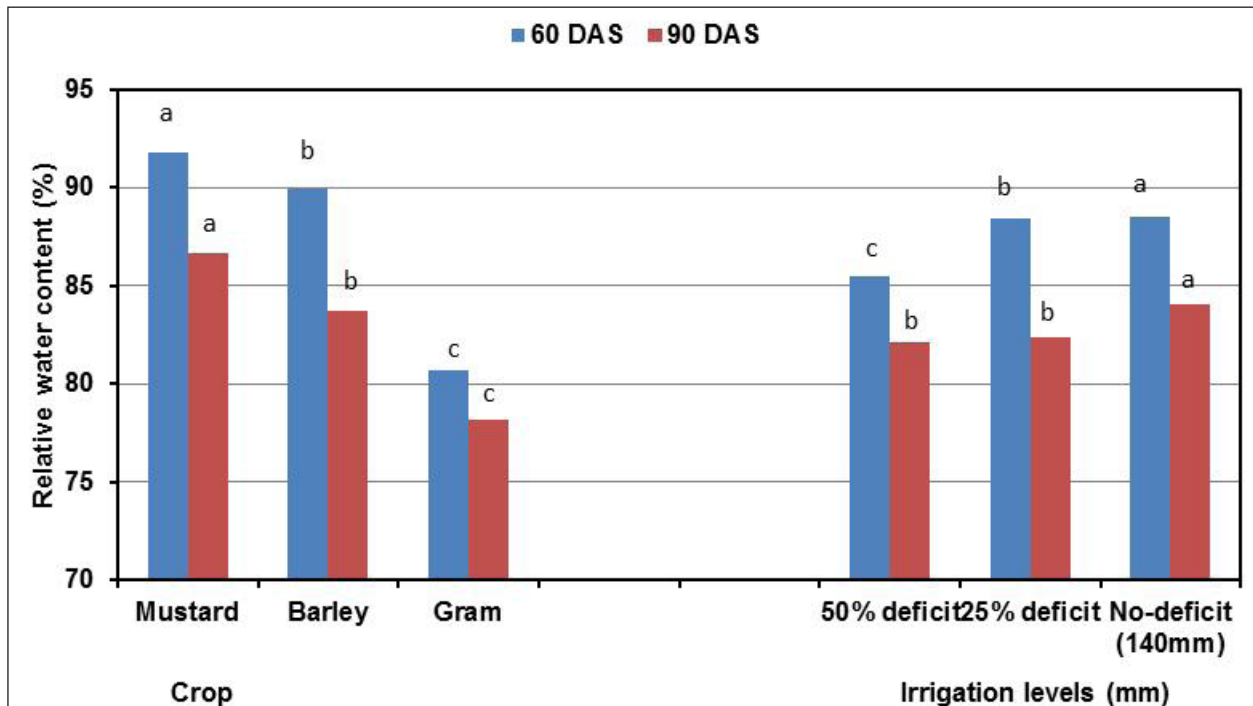


Fig. 6. Relative water content in the leaves of rabi crops received deficit irrigation levels during different growth stages (average of two years) (values within a column for each variable followed by different letter are significantly different at $P < 0.05$).

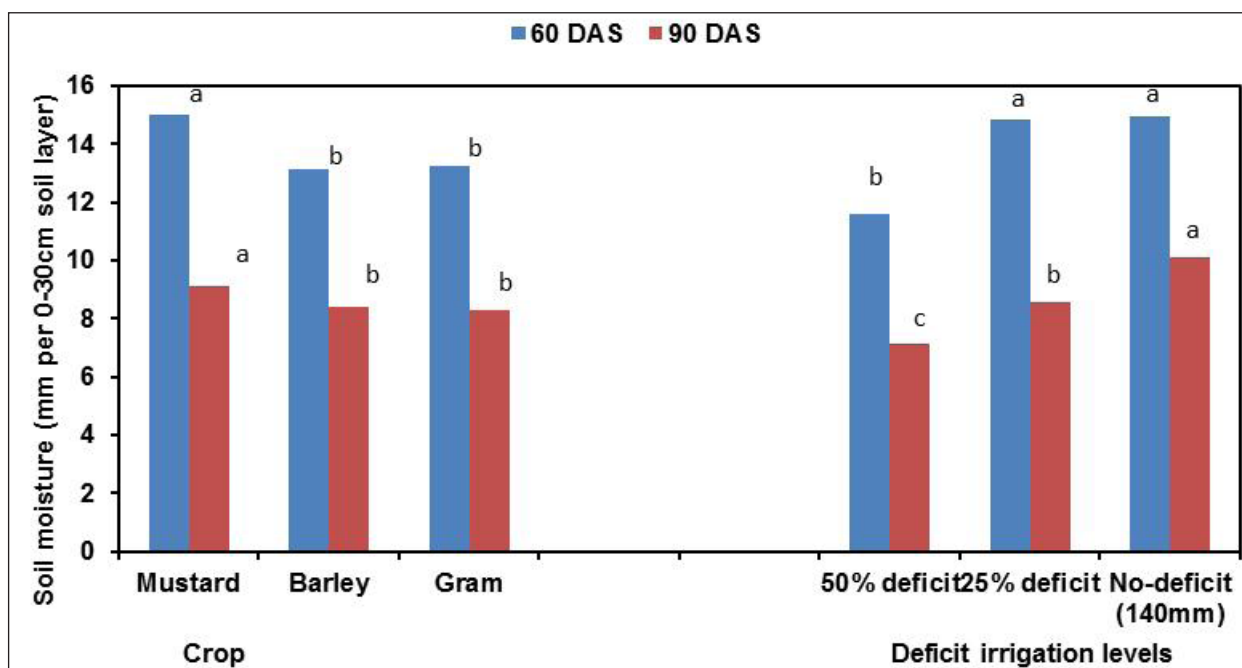


Fig. 7. Soil moisture (mm per 0-30 cm soil layer) under rhizosphere of different rabi crops (average of two years) (values within a column for each variable followed by different letter are significantly different at $P < 0.05$).

at 60 and 90 DAS. The behavior of RWC with deficit levels of irrigations is in accordance with the levels of irrigation water applied in the study and more soil moisture with no-deficit irrigation recorded significantly higher RWC over deficit irrigations.

Soil water content

Soil water content was affected significantly with the crops grown and levels of irrigation (Fig. 7). The rhizosphere of mustard retains more soil moisture during 60 and 90 DAS over barley and gram. The moisture content of 15.02

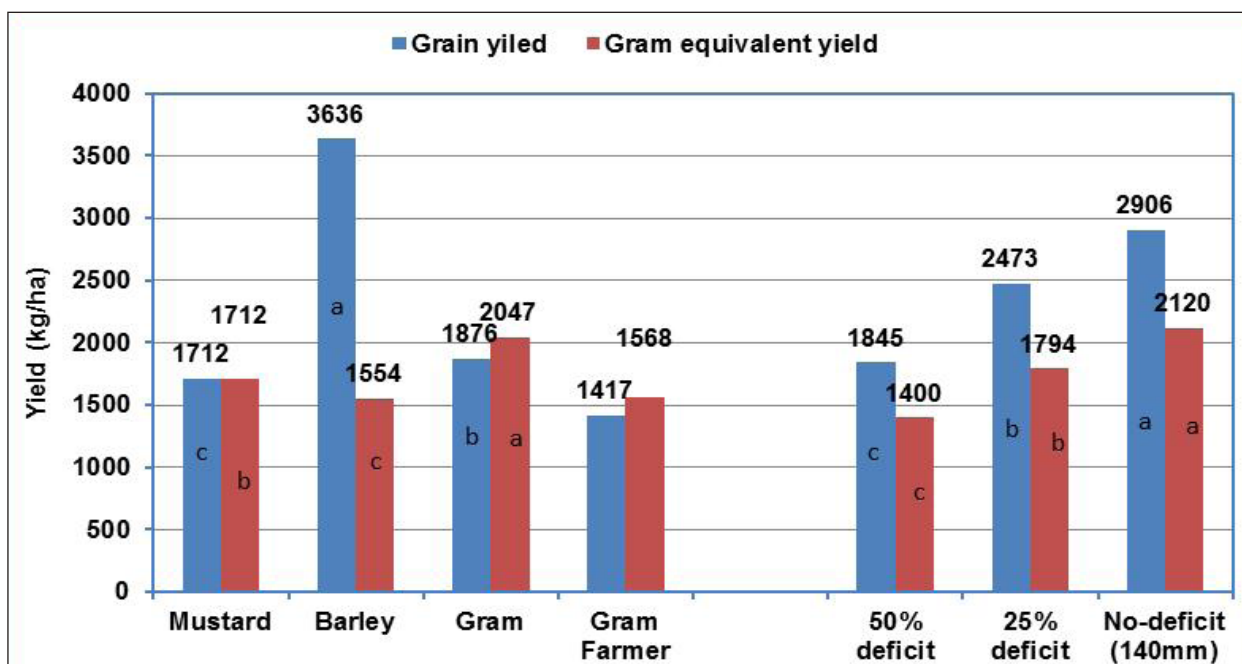


Fig. 8. Grain and gram equivalent yield of crops grown in khadin during rabi (mean of two years) (values within a column for each variable followed by different letter are significantly different at $P < 0.05$).

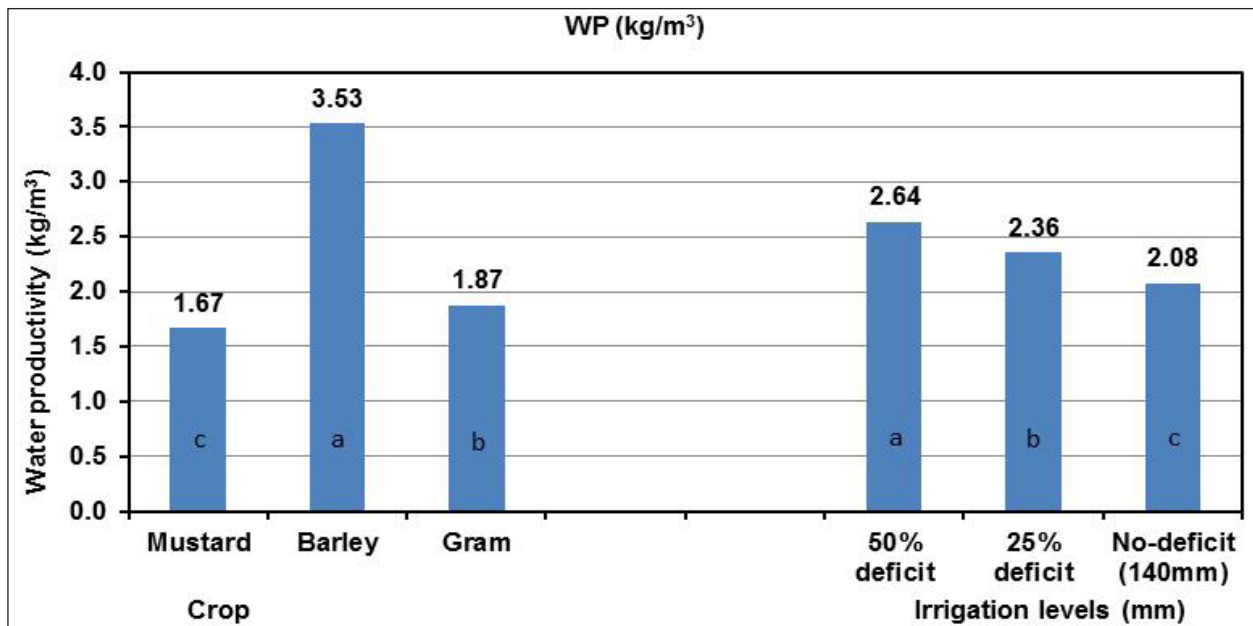


Fig. 9. Water productivity of crops grown in khadin during rabi (mean of two years) (values within a column for each variable followed by different letter are significantly different at $P < 0.05$).

mm and 9.14 mm ($0-30 \text{ cm}^{-1}$ soil layer) was recorded with mustard which was 13 and 10% higher than the gram and 14 and 9% higher than barley at 60 and 90 DAS. Both barley and gram recorded at par soil moisture during 60 and 90 days crop growth stages. For deficit irrigation levels, significant difference in soil water content was displayed in the 0-30 cm soil layer. Across growth stages no-deficit irrigation

level recorded significantly higher soil water content than the 50%-deficit and 25%-deficit levels of irrigation.

Yield and water productivity

The grain yield of 3636 kg ha^{-1} was recorded with barley which was 112 and 94% higher than the mustard and gram respectively (Fig. 8). However, in terms of gram equivalent yield

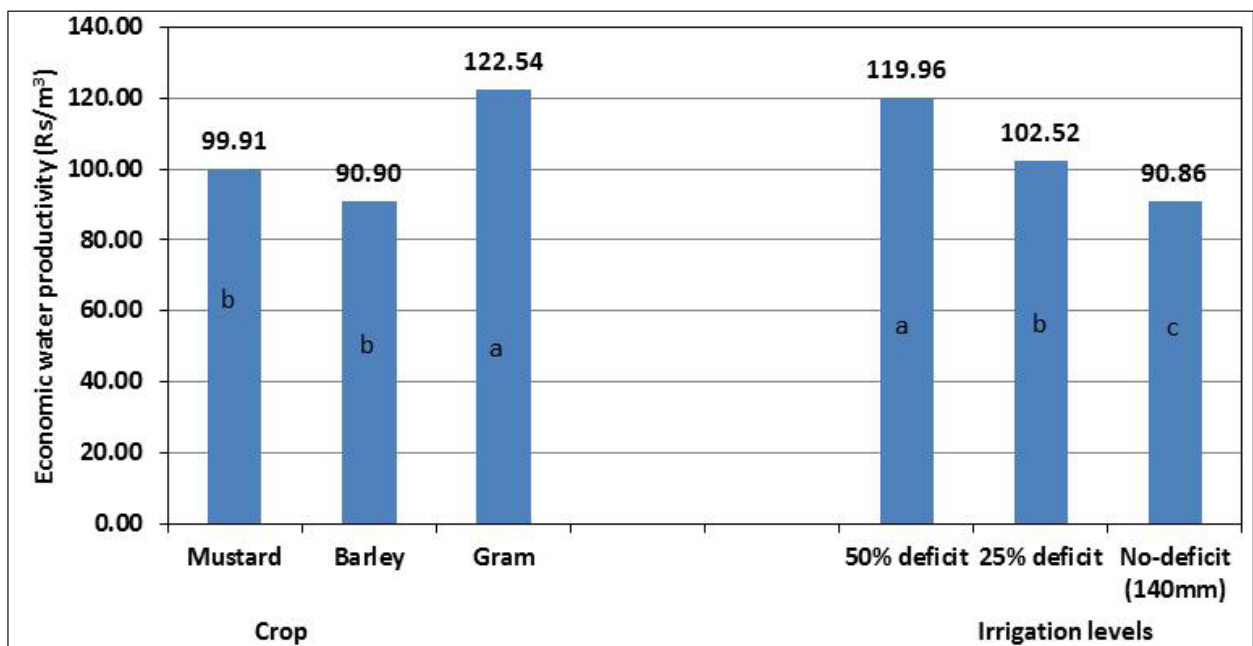


Fig. 10. Economic water productivity of crops grown in khadin during rabi (mean of two years) (Values within a column for each variable followed by different letter are significantly different at $P < 0.05$).



Fig. 11. A view of runoff storage structure within khadin of Ajeet Nagar (Jodhpur).

(GEY), gram recorded 2047 kg ha^{-1} which was 32 and 20% higher than barley and mustard. The farmer-grown gram on conserved soil moisture recorded GEY of 1538 kg ha^{-1} which was lower by 479 kg ha^{-1} than the gram grown with supplementary irrigation. The reduction in irrigation water from no-deficit to 25%- and 50%-deficits caused yield reduction to the tune of 17.51 and 57.51% of grain yield and 18.17 and 51.43% gram equivalent yield, respectively.

Crops and irrigation levels had significant effect on water productivity (WP) in terms of irrigation water applied (Figure 9) and economic water productivity (EWP) in terms of revenue

gained per unit of water applied (Figure 10). Among crops, barley recorded significantly high WP of 3.53 kg m^{-3} which was 111.37 and 88.77% higher than the mustard and gram. Gram crop also recorded significantly higher WP over mustard. The reduction in irrigation numbers increased WP progressively and 50%-deficit level of irrigation recorded highest WP (2.64 kg m^{-3}) which was significantly greater and had advantage to the tune of 11.86 and 26.92% over 25%-deficit and no-deficit levels, respectively. The similar trend of EWP was observed with the levels of irrigation but showed converse trend with crops. The highest EWP of 122.54



Fig. 12. A field view of crop grown within khadin with supplementary irrigation using stored runoff at Ajeet Nagar (Jodhpur).

(Rs. m⁻³) was observed with gram which had advantage of Rs 31.65 m⁻³ of water applied over barley. The mustard and barley crops remained at par with respect to EWP. The application of extra 10,000 liter water (cubic meter water ha⁻¹) with successive irrigation levels of 25% and no-deficit caused reduction in economic gain of Rs. 17.45 and 29.10, respectively.

Discussion

Rain drops of Rajasthan have been called 'silver drops' and these precious drops are conserved by the farmers of the Thar desert for agriculture through the traditional rainwater harvesting system of *Khadin*. Traditionally farmers did not apply ground water for supplementary irrigation to crops. However, in some of the older *khadins* of Jaisalmer; Rupsi, Masurdi, Brahmsar, Bhajka, etc., tube wells facilities were created for irrigation of these *khadin* beds. The groundwater quality in most of the *khadins* is very poor and continuous irrigation had created soil sodicity problems resulting in lower crop productivity. The creation of runoff storage structures at suitable point help in preventing exploitation of poor quality ground water and also prevented further deterioration of *khadins*. In the present study runoff storage structures (Fig. 11) lined with 300 micron HDPE sheet was constructed within *khadin* that stored 3.2 million litres surplus runoff and irrigations were given to crops (Fig. 12) through mini-sprinklers powered by 2HP solar pump for enhancing productivity of these landforms.

The crop yield and water productivity (WP) are affected by climate, crop species, soil, crop management and choice of crop (Santra *et al.*, 2021). Among agronomic practices, irrigation affected WP to the extent of 32.8% (Li *et al.*, 2016). The increased availability to crops had positive effect on the photosynthetic apparatus. There exists a relationship between chlorophyll content and leaf senescence and higher content of chlorophyll delayed leaf senescence (Genard *et al.*, 2017). Since barley and gram retained more leaves compared to mustard is the reason for higher chlorophyll content during both crop growth stages. This result suggests a delay in leaf chlorophyll degradation (especially for old leaves), which can be explained by a delay in leaf senescence (Malagoli *et al.*, 2005). Both Chlorophyll "a" and chlorophyll "b" is the

site of photo-chemical reaction and absorbs light required for photosynthesis. Chlorophyll "a" is considered the primary photosynthetic pigment and chlorophyll "b" assisted in supplying more light energy to chlorophyll "a". Flowering plants have more chlorophyll "a" as compared to chlorophyll "b" for survival. Further, chlorophyll "a" was reported to be more sensitive to abiotic and biotic stresses compared to chlorophyll "b" (Mafakheri *et al.*, 2010). Though the total chlorophyll content was recorded significantly higher with barley, the lowest ratio of both these pigments was recorded with this crop indicating that it is more sensitive to moisture stress compared to gram and mustard and traditionally farmers are preferring gram and mustard during low rainfall years in the *khadins* over wheat/barley (Prasad *et al.*, 2004). The superiority of gram in maintaining higher chlorophyll content despite lower relative water content compared to barley indicated that it is more tolerant to moisture stress. The presence of salicylic acid in gram is considered responsible for this since salicylic acid plays an important role in the growth and development of the plant for important physiological roles such as increasing the plant's response to stress conditions (biotic and abiotic) by increasing the resistance of the plant to System Acquired Resistance (SAR) (War *et al.*, 2011).

The soil moisture dynamics is affected by many factors including rooting pattern of crops grown. In the study more soil water content in the mustard rhizosphere was attributed to vigorous rooting pattern of this crop compared to barley and gram. Earlier researches conducted with mustard and lentil reported that mustard had taken up only 55% soil water from the 0-30 cm soil depth as compared to lentil and mustard had taken rest of the soil water from deeper soil layers (Kumar *et al.*, 2018). Similarly, Cutforth *et al.*, 2013 also reported that pulses absorbed substantially less water than oilseeds below about the 80 cm depth and oilseeds absorbed less water than wheat from the upper regions of the soil profile. Further, crops required more soil water during grain filling phase (Thorup-Kristensen and Kirkegaard, 2016) and thus lower soil water at 90 DAS can be attributed to more uptake of soil moisture by the crops, depletion of soil moisture due to evapotranspiration and percolation.

In our study, legume crop recorded higher GEY because of economic use of crop by-product straw as animal fodder compared mustard and higher economic importance of gram grain (Rs. 60 kg⁻¹) over barley (Rs. 20 kg⁻¹) despite similar economic significance of barley straw as animal fodder. The higher grain yield with barley was attributed to more content chlorophyll in its during both crop growth stages compared to mustard and gram which was consistent with recent reports by other researchers (Oikawa and Ainsworth, 2016). The yield decline with reduction in irrigation water in the study could be attributed to decrease in physiological functions (Figs. 4 and 5) resulting in associated decrease of dry matter production. The results of the study are in line with those observed by Rathore *et al.*, 2021 in groundnut under similar conditions of arid environment. The higher WP with barley was attributed to higher chlorophyll content in the leaves that delayed senescence of leaves and thus more harvesting of solar radiation into dry matter production (Oikawa and Ainsworth, 2016). The applied irrigation water with 50%-deficit was reduced by 100% compared to no-deficit irrigation whereas yield was reduced only around 57.51% (Fig. 8) and because of this 50%-deficit level recorded greater WP and EWP in the study.

Conclusion and recommendations

The study couples *khadin* with a lined rainwater harvesting structure and recycling water using farmer-led solar-powered irrigation systems. This method allows for better control over when and how much water is used, thus, allowing farmers to grow highly profitable crops such as fruits and vegetables that are sensitive to water stress. From the study it was observed that supplementary irrigation at grain formation stage from the stored runoff water increased the water productivity to the tune of 2.64 kg m⁻³ which is comparable or higher than the areas that have good irrigation facilities. Further, in the conserved soil moisture crops selection of crops in terms of economic water productivity (EWP) is important and gram produced highest EWP of Rs. 122.54 m⁻³ which is much higher than the other field crops. The findings of the study are needed to be extended in the existing 500 *Khadins* of Jaisalmer and 131 *khadins* of Jodhpur district for improving farm income and livelihood of the peasants.

For irrigating experimental area, only 235,500 litre water was consumed and 1.46 million litre water remained available in storage structures that can be used for irrigating additional rabi crops on 4.0 ha or for growing summer cucurbit crops in succession of rabi crops during February to May. However, cucurbit crops not produced fruits in the *Khadin* situation during both years of study. The best alternative for this water is growing of green fodder as there is acute shortage of fodder during April to May in Indian arid zone. Similarly, stored water can also be used for watering of horticultural plants grown on the *Khadin* bunds for getting additional farm income.

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