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Micro-irrigation and fertigation improves gas exchange, productivity traits and economics of Indian mustard (*Brassica juncea* L. Czernj and Cosson) under semi-arid conditions

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Abstract

An experiment was conducted to evaluate the effect of micro-sprinkler and drip irrigation with nitrogen fertigation on gas exchange traits, growth, yield and economics of Indian mustard during 2009-10 and 2010-11 under semi-arid conditions of Rajasthan, India. The experiment was conducted in split plot design, consisting of five irrigation systems in main plot *viz*. MS, MS+CB, DS, DS+CB and CB alone. Four nitrogen levels (N) 0, 40, 80 and 120 kg ha^{-1} were taken in the sub plots. The results revealed that MS and DS alone or in combination with CB influenced the physiological parameters including chlorophyll concentration, PAR, ICC, photosynthesis, transpiration and stomatal conductance. The regular moisture supply throughout the crop period improved the yield attributes like primary and secondary branches, main shoot length, total siliquae and 1000 seed weight. The mustard seed yield increased by 24 % due to MS and by 18 % due to drip irrigation over check basin during the two years. Increase in N fertigation levels from 0 to 120 kg ha^{-1} significantly improved mustard yield attributes, seed and oil yield, however, were found at par with 80 kg Nha^{-1} during 2009-2010. This improvement in growth, physiological and yield attributes of mustard due to micro- irrigation and N application significantly enhanced seed and oil yield, production efficiency, sustainable yield index and irrigation water use efficiency. The crop under CB experienced the highest stress index, while it was lowest under MS and MS+CB. The net returns also increased by 45 and 47% respectively with DS and MS over CB. Hence, all micro irrigation systems at every level of N fertigation out yield the effect of CB.

Keywords: *Brassica juncea*, check basin, drip irrigation, fertigation, irrigation water use efficiency, micro-sprinkler, SPAD.
Abbreviations: AGDM_Above ground dry matter; AS_assimilate supply; CB_Check basin; CWSI_Crop water stress index; DS_Drip system; ICC_Internal CO_2 concentration; MIS_Micro irrigation system; MS_Micro-sprinkler; N_Nitrogen; P_Phosphorus; PAR_Photosynthetically active radiation; PE_Production efficiency; RUE_Radiation use efficiency; REE_Relative economic use efficiency; SPAD_Soil plant atmosphere development system; SYI_Sustainable yield index, WUE_Water use efficiency.

Introduction

By 2050, India needs to produce 17.84 million tonnes of vegetable oils for its nutritional fat requirement of projected 1685 million population. This target is difficult to achieve at current status of technology and resources management in Indian agriculture (Hegde, 2012). Thus, enhancing the productivity of oilseeds is imperative for self-reliance. India holds 11.3 % of world's arable land and only 4% of the water resources to feed 16% of human population and 18% of animal population of the world. The decreasing availability of water to agriculture sector has become a serious limitation in many areas, particularly in semi-arid areas. The share of water for agriculture is expected to reduce further with the increasing demand from other sectors. This necessitates efficient use of water and nutrients to enhance the productivity of edible oilseeds. And to counter the deficit without missing the production targets, adoption of micro-irrigation system (MIS) in 4.9 Mha of the total area under oilseeds in India is recommended (DOAC, 2004). Among edible oilseeds, rapeseed-mustard has the distinction of highest national productivity of 1145 $kgha^{-1}$ in India. The area and production of rapeseed-mustard were 5.92 Mha and 6.78 Mt during 2011-12 (DOAC, 2012). Although, 75.5% of rapeseed-mustard area in India is irrigated, but the faulty irrigation methods and scheduling leads to low productivity and water use efficiency from irrigated area. In India, 85-90% of total rainfall is received during rainy season (July-September) and Indian mustard is grown during winter season (October- March) on conserved moisture (Ghosh et al., 2002). The limited available water is applied mainly though check basin, where water use efficiency (WUE) seldom exceeds 35-40%. One time application of irrigation water results in excess water supply at one growth stage and moisture stress at another, affecting growth and photosynthesis, subsequently reduces yield attributes like primary and secondary branches, main shoot length, number and length of siliqua and seed yield of Indian mustard (Singh et al., 1991; Mandal et al., 2006). Nitrogen in an essential element but its use efficiency is very low (30-40%). Unlike phosphorus, the unutilized N is not stored in the soil but is lost through volatilization, leaching and runoff. A potential quantity of N is leached under check basin irrigation system where water supply exceeds evapo-transpiration (Katyal et al., 1985). Fertigation ensures a regular, uniform and timely supply of N without environmental contamination through leaching (Asad et al., 2002). Adaptive advantages of mustard to water and nutrient stress has been reported by Wright et al.

(1996), but the effect of micro irrigation and N fertigation on growth, yield and water use efficiency has not been reported adequately. Hence, the field experiments were conducted to evaluate the effect of micro irrigation and N-fertigation on growth, yield, oil production, sustainability and irrigation water use efficiency of Indian mustard (*Brassica juncea* cv. *Rohini*) during 2009-10 and 2010-11 under semi-arid conditions of Rajasthan, India.

Results and Discussion

Gas exchange traits

Adsorbed photosynthetically active radiation (APAR), internal CO_2 concentration (ICC), photosynthetic rate, transpiration rate, stomatal conductance and evapo-transpiration were recorded during 2009-10 and 2010-11 (Table 2). The irrigation systems and levels of N fertigation significantly influenced various physiological parameters of mustard. The micro-irrigation treatments, *viz*. MS and DS increased the adsorption of PAR by 23% and 18% respectively over CB due to higher canopy expansion. The PAR adsorption under MS was recorded 4.5% and 4.2% higher than DS during 2009-10 and 2010-11 respectively. The similar observations were recorded for ICC, photosynthetic rate, transpiration rate and stomatal resistance during both the years. A higher internal CO_2 concentration to ambient CO_2 results in increased photosynthetic rate due to higher CO_2 assimilation at the tissue level. The highest rate of photosynthesis was recorded under MS alone, followed by MS+CB due to favourable canopy architectural parameters like leaf expansion, orientation and leaf area duration. At the leaf level, stomatal regulation of gas exchange has an important role in determining the rate of CO_2 diffusion into the leaf for photosynthesis and the rate of water loss in transpiration (Jones, 1992). The rate of transpiration is influenced by two main canopy architectural parameters *viz.* the foliage inclination distribution in space i.e. projection function and the aggregative nature of canopy elements i.e. the clumping function (Govind et al., 2013). Both these functions are strongly influenced by the distribution of moisture in the soil and hence the method of irrigation. That is the reason; the rate of transpiration was recorded highest under MS, DS and MS+CB being at par with it. The transpiration rate is dependent on the humidity gradient between the leaf's internal air spaces and the outside air. The higher humidity created in the micro climate of the crop through micro sprinkler is responsible for lower transpiration rate in the same. Stomatal conductance measures the rate of passage of CO_2 entering and the water vapor exiting. It is directly related to the absolute concentration gradient of water vapor from the leaf to the atmosphere. Stomatal conductance has proven to be important in determining the amount and efficiency with which water is used by crops and the productivity of those crops (Condon et al., 2008). The stomatal conductance was highest under of MS+CB because the good water availability allowed the development of dense canopies exerting a relevant aerodynamic resistance on water vapor fluxes. Similarly, the atmospheric humidity was highest through higher evaporation and transpiration from this treatment. On the contrary, the rate of evapotranspiration was highest under CB due to less proliferated canopy, more exposed ground area and low plant count per unit area of land. The similar trend was observed during the second year on these physiological parameters under irrigation systems. Approximately, 99% of the water taken up by the plant root is transpired to the atmosphere through stomata. Successive increase in N doses gradually and significantly influenced the light interception and its relationship with the biochemical and physiological traits of mustard. The highest values of adsorbed PAR, ICC, photosynthetic rate and stomatal conductance were recorded at 120 kg N ha^{-1} (Table 1). The accumulation of soluble nitrogen, sugars, starch and proline under high N doses increased internal CO_2 concentration and net photosynthesis (Sharma and Ramachandra 1990; Singh and Singh 1984). Net photosynthesis and stomatal conductance are strongly related. Increase in concentration of internal CO_2 results in decreasing stomatal resistance and hence higher stomatal conductance. When radiation is not limiting, nutrition and water are the major factors that influence stomatal conductance, unless the leaves are not senescing (Denmead and Millar, 1976). Also, the stomatal conductance is integral to leaf level calculations of transpiration. Hence, the rate of transpiration and stomatal conductance were highest under 120 kg N ha^{-1}. The higher availability of nitrogen to crop increased evapo-transpiration but improved transpiration efficiency (Regar et al., 2006).

Differential chlorophyll levels (SPAD units)

The leaf chlorophyll concentration is an important parameter that is measured as an indicator of photosynthetic potential. SPAD meter is a portable simple and nondestructive chlorophyll meter suitable to use for the estimation of relative leaf chlorophyll content of plants (Díaz et al. 2010). The relative chlorophyll contents, as measured by the SPAD meter, were consistently higher for MIS as compared to CB (Table 2). The higher SPAD units observed for MS and DS are likely associated with the more efficient N uptake and better photosynthetic leaf function, especially during late seed filling which leads to a longer ‘‘stay-green’’ period, longer seed-fill interval and corresponding higher seed yield (Kumar and Pandian, 2010). During both the years, the SPAD values gradually increased with higher levels of N fertigation. Nitrogen has a direct role in synthesis of chlorophyll and uptake of other nutrients and therefore, higher N levels resulted in better chlorophyll concentration and more SPAD values (Turner and Jund, 1994; Peng et. al., 1995; Balasubramanian et al., 1999).

Days to 50% flowering

One of the most important traits for cultivated plants is the timing of the transition from vegetative to reproductive growth (flowering time). This transition from vegetative to reproductive stage is affected by environmental factors (especially, temperature and soil moisture) and signals within the plant. Flowering time reflects the adaptation of a plant to its environment by tailoring vegetative and reproductive growth phases to local climatic effects (Machikowa and Laosuwan, 2009). Later flowering has been reported to be associated with higher yield (Dunphy et al., 1979). Therefore, the extension of days to flowering may result in higher yields. Different irrigation systems resulted in significant variation in commencement of flowering. Maximum days to

Table 1. Gas exchange traits of Indian mustard (cv. Rohini) as influenced by irrigation systems and N fertigation.

Treatments	Photo synthetically active radiation (µ mol $m^{-2}s^{-1}$)		Internal CO_2 concentration (ppm)		Photosynthetic rate (µ mol $m^{-2}s^{-1}$)		Rate of transpiration (mmol $m^{-2}s^{-1}$)		Stomatal conductance (mmol $m^{-2}s^{-1}$)		Evapotranspiration (mm)	
	2009-10	2010-11	2009-10	2010-11	2009-10	2010-11	2009-10	2010-11	2009-10	2010-11	2009-10	2010-11
Irrigation systems												
CB	590^{c}	621^{c}	346^{c}	346^{c}	8.3^{d}	9.2^{d}	19.2^{c}	19.2^{b}	46.6^{a}	46.8^{c}	4.5^{c}	4.9^{d}
DS	699^{b}	731^{b}	348^{b}	348^{b}	9.2^{c}	10.3^{c}	22.1^{a}	22.1^{a}	46.4^{a}	46.6^{c}	4.6^{c}	4.4^{c}
MS	731^{a}	762^{a}	352^{a}	353^{a}	10.1^{a}	11.2^{a}	21.9^{ab}	21.8^{a}	48.0^{b}	48.2^{a}	3.9^{a}	3.6^{a}
MS+CB	703^{b}	734^{b}	346^{c}	346^{c}	9.5^{b}	10.6^{b}	21.7^{b}	21.7^{a}	50.2^{d}	50.5^{b}	4.2^{b}	4.2^{b}
DS+CB	696^{b}	728^{b}	354^{a}	354^{d}	9.5^{b}	10.6^{b}	19.6^{c}	19.5^{b}	48.8^{c}	49.0^{d}	4.8^{d}	4.8^{c}
Fertigation of N (kg ha^{-1})												
Control	481^{a}	513^{a}	338^{a}	339^{a}	6.9^{a}	8.0^{a}	16.4^{a}	16.3^{a}	43.7^{a}	43.8^{a}	3.3^{a}	3.4^{a}
40	599^{b}	631^{b}	345^{b}	346^{b}	8.1^{b}	9.2^{b}	19.2^{b}	19.1^{b}	45.0^{b}	45.2^{b}	4.0^{b}	4.0^{b}
80	716^{c}	748^{c}	350^{c}	351^{c}	10.0^{c}	11.1^{c}	22.8^{c}	22.7^{c}	50.0^{c}	49.7^{c}	4.8^{c}	4.8^{c}
120	938^{d}	970^{d}	354^{d}	355^{d}	12.4^{d}	13.3^{d}	25.2^{d}	25.2^{d}	54.0^{d}	54.1^{d}	5.4^{d}	5.4^{d}

Note: Within column, value represents with different letter indicate significant difference ($P \leq 0.05$)

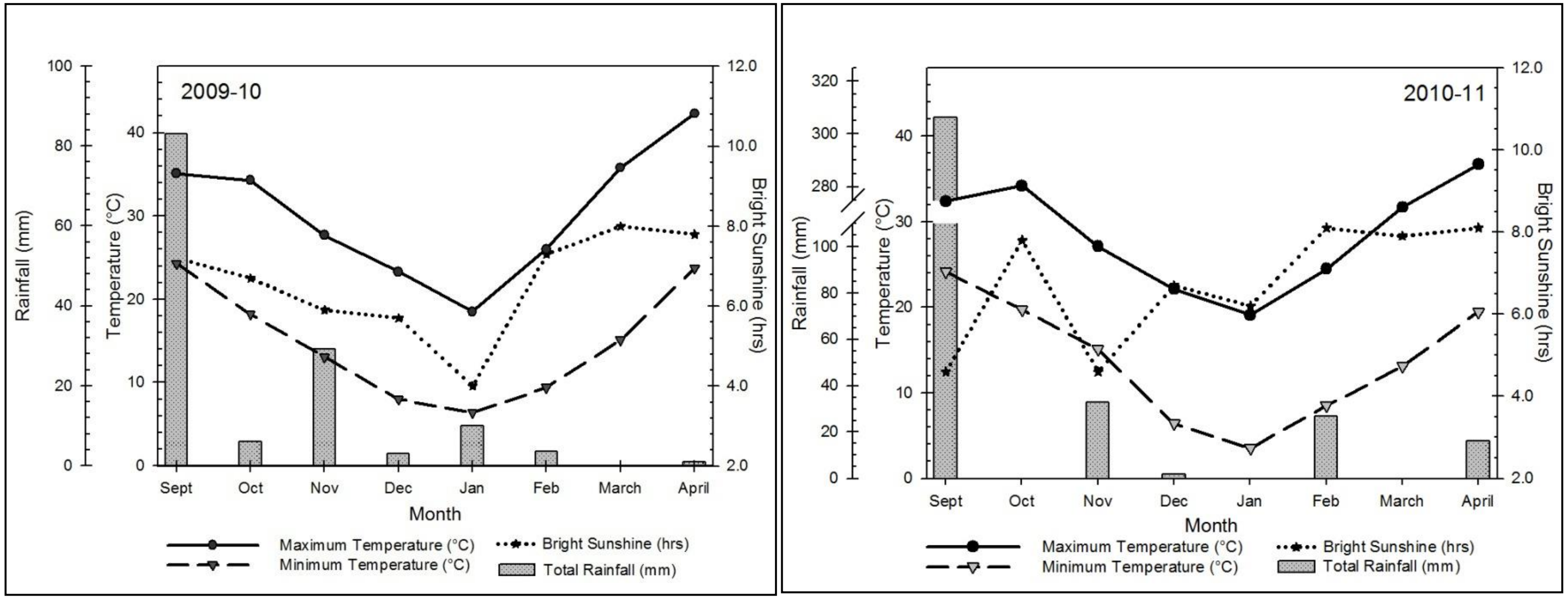

Fig 1. The variation in weather parameters during 2009-2010 and 2010-2011. The sudden decrease in bright sunshine hours and higher temperature at terminal growth stage reduced yield during 2009-2010. The rainfall in February and higher sunshine hours during seed filling stage increased seed yield during 2010-2011.

50 % flowering were observed in MS during both the years. Micro-irrigation treatments were successful to increase days to flowering, hence increasing the total photoperiod while keeping the days from flowering to maturity intact. It enabled the crop to accumulate higher biomass to sustain a high yielding potential. Fertigation of N doses recorded reverse trends in days to 50% flowering and minimum days were required with higher N levels (120 kg/ha).

Yield attributes

The MIS significantly improved the yield attributes of mustard as compared to CB (Table 2). Irrigation through DS and DS+CB increased primary branches significantly by 38.7% and 29.8% over CB during 2010-11. The number of secondary branches was obtained highest under MS alone, MS+CB and DS+CB being at par with it. The MS alone increased secondary branches significantly by 23.5% during 2009-10 and by 44.1% during 2010-11. Main shoot length is an important yield attribute in mustard. The longest main shoot was produced under MS during both the years of the experimentation, MS+CB being at par with it during 2009-10. Drip system and DS+CB produced significantly more siliqua on main shoot than CB during 2009-10 while all the micro-irrigation treatments except DS+CB were superior to CB during 2010-11. Over all, MS+CB produced 36% higher siliqua plant^{-1} than CB and remained statistically at par with MS and DS during 2010-11. The MS+CB produced highest number of total siliquae plant^{-1}, MS being at par with it during both the years. The number of seeds siliqua^{-1} ranged from 14.2 to 16.1 throughout the experiment. An inverse relationship has been recorded in 1000 seed weight and number of seeds siliqua^{-1}. Hence, it was recorded highest in DS, MS+CB being at par with it. The greater radiation use-efficiency under micro irrigation treatment is associated with its greater stomatal conductance in pre-anthesis resulted in a greater biomass and CO_2 assimilation than CB in correspondence with higher amounts of water used. This remarkable greater stomatal conductance of micro-irrigation confers an advantage in terms of both water and radiation use-efficiency resulting in higher yield attributes (Condon et al., 2002). The yield parameters of mustard improved with the subsequent doses of N in the form of fertigation up to 120 kg Nha^{-1}. But the response of mustard for the all yield attributes except total siliquae plant^{-1} at 80 kg Nha^{-1} was found at par with 120 kg Nha^{-1}. The highest total siliquae plant^{-1} was recorded at 120 kg N ha^{-1} during both the years. In general, the water supply at regular interval under micro-irrigation systems shortened intermittent water stress period faced by the crop, thereby improved soil-plant-water relationship and finally yield attributes (Rao et al., 2010). Fertilization and irrigation strongly increased both APAR and light utilization efficiency because of greater light capture. The stay green qualities in the plants irrigated through micro sprinklers results in increased efficiency of using light for the longer period, resulting in higher yield attributes and yield (Fischer et al., 1998).

Biological, seed and oil yield

In general, mustard seed yield in 2010-11 was higher than 2009-10 due to timely onset and periodic rainfall. A careful study of the meteorological data (Fig 1) reveals that the weather parameters played a crucial role in influencing growth, yield attributes and yield of mustard. The weather data for two years revealed distinct variation in minimum and maximum temperature, rainfall and sunshine hours in two cropping seasons. A significant difference was found in both the cropping seasons for heat unit accumulation. The higher maximum temperature during the seed filling stage and the assimilate accumulation period, caused forced maturity in the first year. The crop yield is one of the most sensitive economic trends to higher temperature, especially during seed filling stage (Brown and Plan, 2006). Crops like mustard in India is grown at or near their thermal optimum, making them vulnerable to any rise in temperature. Higher temperature can reduce or even halt photosynthesis, prevent pollination and ultimately lead to crop dehydration. During critical crop growth phases in the development of mustard, such as pod formation and seed setting, the transgression of high temperature thresholds can reduce the number of seeds that subsequently contribute to crop yield. A few days of higher temperature are sufficient to have a potentially large impact on yield (Challinor, 2004). The mustard was sown on the conserved soil moisture during both the years. Hence, a relatively higher rainfall during September in the second year helped the crop in early establishment with an initial advantage. Also, the rainfall in February coincided with the second irrigation, when the crop was at pod setting and seed filling stage. It helped the plant to synthesize higher pods per plant and more number of seeds per unit area during the second year. Mustard requires cool weather from seedling stage to flowering stage and warm and sunny days during flowering to maturity, which was a reason for higher yield in 2010-11. Low yield in 2009-10 could be due to high humidity, rains during January accompanied with low sunshine hours at the time of flowering (January and February) which resulted in poor seed set. Fertigation permits improved efficiency of irrigation and nutrient use and reduces application costs (Anitta Fanish et al., 2001). During crop growth, supply of nutrients and availability of assimilates for pod set and seed filling are decisive factors affecting yield. For Indian mustard, the sink lies in the siliqua and seed and hence, under optimum supplies of N this greater translocation of photosynthates from leaf to siliqua resulting in robust siliqua and seeds (Hocking et al., 1997). Fertigation of 40 kg Nha^{-1} significantly increased the seed yield by 13.9% during 2009-10 and by 40.7% during 2010-11 over no fertigation (control). Higher N doses through fertigation up to 80 kg Nha^{-1} enhanced the seed yield by 37.7% during 2009-10 and by 60.8% during 2010-11 over control. Fertilization of N substantially increase productivity of mustard by increasing stand leaf area index and the efficiency of converting intercepted light into biomass of the individual plant. The growth response is the summation of individual plant responses and hence higher yield was obtained under higher N doses (Otavio et al., 2012). The variable N doses bring variation in stomatal conductance which is reflected in terms of radiation use efficiency (RUE). Nitrogen supply results in interception of light and plant photosynthesis, nutrient supply and biomass partitioning. This promotes higher biomass because of enhancement in morphological characteristics such as the size and number of stomatal pores, which are sufficient to generate differences in the rate of carbon gain. This also helps to explain the positive association often observed between high stomatal conductance and grain yield and biomass (Sayre et al., 1995). Nitrogen stimulates plant growth by means of enlarged leaf canopy and a greater rate of leaf expansion, resulting in higher pods (Write et al., 1988; Dipenbrock, 2000) and higher seed number per pod (Allen and Morgan, 1972; Rood and Major, 1984), possibly because of increased meristematic activity and development of more flowers and siliqua (Patel and Meisheri, 1997). Seed yield

Table 2. Growth and yield attributes of Indian mustard (cv: Rohini) as influenced by irrigation systems and N fertigation.

Treatments	SPAD		Days to 50% flowering		No. of primary branches		No. of secondary branches		Main shoot length (cm)	
	2009-10	2010-11	2009-10	2010-11	2009-10	2010-11	2009-10	2010-11	2009-10	2010-11
Irrigation systems										
CB	43.5[c]	42.8[c]	59.0[b]	60.1[b]	6.9[a]	3.7[a]	8.1[b]	5.9[a]	75.5[a]	79.5[ab]
DS	44.2[b]	44.2[b]	59.6[b]	58.0[c]	6.9[a]	4.8[b]	9.7[a]	6.3[b]	79.5[a]	81.9[bc]
MS	44.7[a]	45.6[a]	60.4[a]	61.1[a]	7.6[a]	4.4[a]	10.0[a]	8.5[c]	85.4[b]	88.9[d]
MS+CB	44.6[a]	43.5[bc]	58.8[bc]	57.8[c]	7.1[a]	4.4[a]	9.2[ab]	8.2[c]	80.9[ab]	76.7[a]
DS+CB	44.1[b]	43.8[c]	58.7[bc]	59.5[b]	7.1[a]	5.1[b]	9.2[ab]	8.1[c]	76.2[a]	84.2[c]
Fertigation of N (kg ha^{-1})										
Control	38.5[a]	36.6[a]	63.2[a]	64.0[a]	6.8[a]	3.4[a]	6.7[a]	4.4[a]	74.0[a]	72.8[a]
40	44.1[b]	43.8[b]	61.3[b]	62.3[b]	6.8[a]	4.1[ab]	9.5[b]	6.5[b]	79.3[b]	81.9[b]
80	45.7[c]	46.0[c]	57.1[c]	58.0[c]	7.8[b]	4.8[bc]	10.9[c]	9.4[c]	83.1[b]	85.5[c]
120	48.3[d]	49.5[d]	55.5[d]	56.0[d]	7.0[a]	5.5[c]	9.9[bc]	9.7[c]	81.2[b]	88.9[d]

Note: Within column, value represents with different letter indicate significant difference (P≤0.05)

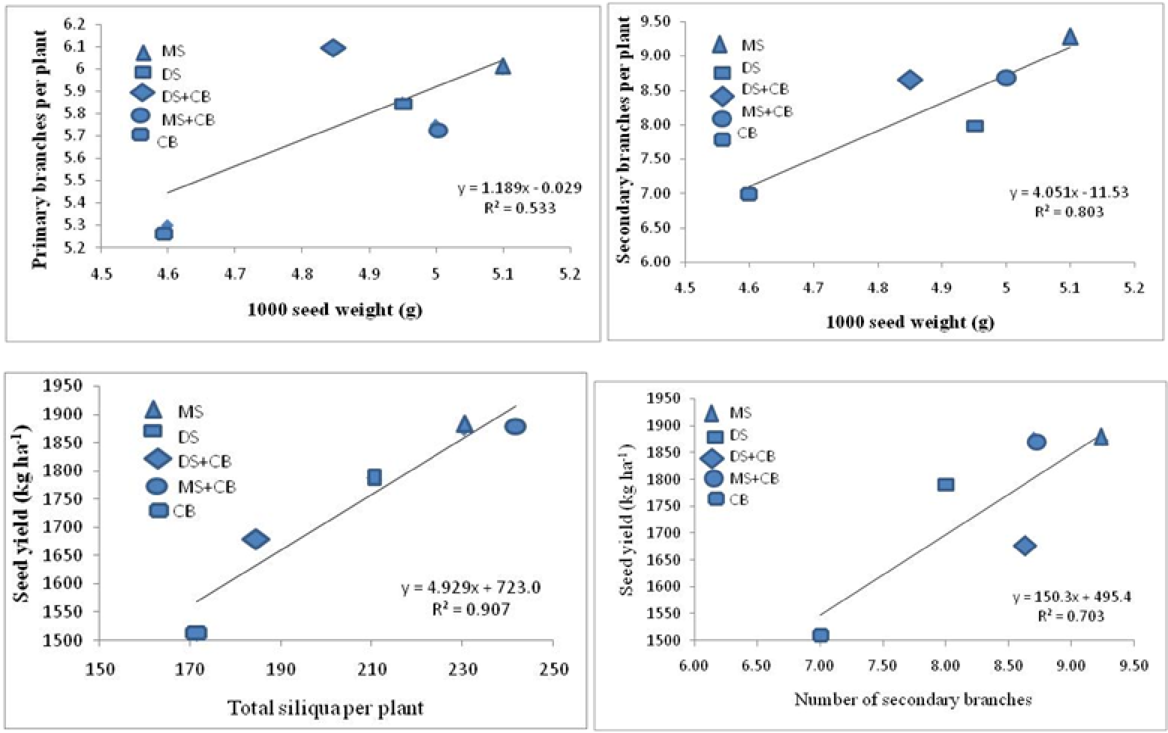

Fig 2. Dependence of seed yield on yield attributes of mustrad under micro irrigation systems (pooled dataof 2 years). The 1000 seed weight of mustard in more influenced by the number of secondary branches than the number of primary branches. Total seed siliquae per plant and number of secondary branches increased under micro-irrigation systems. R^2 is the determination coeffecient.

can be increased by simultaneous increase in the capacity of the sink and the source for seed filling. Further increasing the fertigation levels to 120 kg Nha^{-1} significantly enhanced the seed yield over 80 kg Nha^{-1} by 11.79% during 2010-11. Biological yield and oil yield followed a similar trend. The oil yield was obtained highest with 120 kg N ha^{-1} during both the years. Nitrogen plays an important role in protein balance, oil biosynthesis and maintaining oil: protein ratio among oilseed crops (Tripathy and Sawhney, 1989). However, under 80 kg N ha^{-1} the oil yield was found at par with 120 kg N ha^{-1}. The reduction in oil content due to higher N doses was due to the fact that extra available nitrogen enhance degradation of carbohydrates (tricarboxylic cycle) to acetyl CoA, thereby processes of reductive amination and transamination to produce more amino acids (Satyanarayan et al., 1986) causing increased seed protein content with corresponding decrease in seed oil content (Premi et al., 2013).

The leaves shed very quickly after peak flowering, perhaps before nutrients and carbohydrates are remobilized. Hence, the actual yield depends up on the quantity of assimilates that are translocated to the sink, instead of the total dry matter accumulation. A higher assimilate supply under micro irrigation systems are therefore responsible for higher seed yield under these treatments (Table 4). The highest assimilate supply under MS shows that a higher amount of dry matter is required for the synthesis of one siliqua. These higher assimilate supply has a very high correlation with 1000 seed weight and number of seeds per siliqua (Fig 4). Bhargava and Tomar (1990) has suggested a mustard ideotype with few pods but with higher potential number of seeds per pod as this maximizes seed survival and hence increases seed number per unit area. The interaction of the seed yield obtained under various irrigation systems with the N doses indicates that at a given level of N, the yield obtained was higher for MS and DS as compared to CB (Fig 3). Amongst the two MIS, the response was higher for MS due to uniform water distribution in the soil profile. The uniform moisture distribution helps in better growth, higher nutrient uptake and reducing losses which ultimately improves the yield. For the similar response from DS, the distribution of laterals within the rows must be standardized. In the given experiment, one lateral was laid after every 3 rows. It can also be concluded that the crop response to applied nutrient can be enhanced by using micro-irrigation method. In CB, the nutrient loss occurs through leaching and runoff resulting in the higher fertility gradient within the same field.

Production efficiency

Significant variation was observed under various irrigation systems and fertigation in production efficiency during 2009-10 and 2010-11. Relatively higher production efficiency was recorded during 2010-11 over 2009-10 because of prevailing favourable weather conditions. Proper water management through micro-irrigation helps the crop in quick utilization of the readily available nutrients resulting in higher growth and dry matter accumulation which increases the per day productivity of aboveground dry matter (AGDM) of mustard as compared to CB. The MS recorded maximum production efficiency during 2010-11, MS+CB being at par with it. The DS and MS increased the production efficiency by 38.5% over CB. The higher assimilation of metabolizable carbon and N in crop plants due to micro irrigation increased AGDM in addition to increasing root biomass and root absorption surfaces might have increased the production efficiency (Hao et.al., 2008; Makino et al., 1992). In 2009-10, the increase was 23.5% due to MS+CB and 18.5% due to DS+CB. However, during 2010-11, significant increase in production efficiency was observed in MS and MS+CB over CB. For mustard, the response to MS was observed superior over DS possibly because of the configuration of laterals in DS between the mustard rows (3:1). The side rows might have faced some moisture stress at some stage of crop growth. Production efficiency increased with increasing levels of N and maximum production efficiency was recorded at 120 kg Nha^{-1} during 2010-11 but was statistically at par with 80 kg Nha^{-1} during 2009-10 (Table 5). Nitrogen supply to mustard improved the integrity of plant structure and the key physiological processes such as light interception by chlorophyll, energy for carbohydrate build-up and enhanced the hydraulic conductivity of the root cortical cells, thereby improving the biomass accumulation (Dhawan, 2002; Namara et al., 2007)

Sustainable yield index (SYI)

Sustainability of various irrigation systems was estimated during both the years. The nearness of SYI to 1.0 implies the closeness to an ideal situation that can sustain maximum crop yields while deviation from 1.0 indicates the losses to sustainability (Bhindhu and Gaikwad, 1998). The sustainability yield index (SYI) of all the micro-irrigation systems was more than 0.50 reflecting the sustainability of these systems. The increasing level of N fertigation also ensures higher sustainability in the mustard production system due to consistent increase in seed yield. Sustainability index improved from 0.32 of control (no fertigation) to the maximum value of 0.71. Thus higher the levels of N fertigation, more was the sustainability in mustard production system (Table 5).

Water use efficiency

During 2010-11, higher irrigation water use effeciency (WUE_I) and water use effeciency (WUE) was observed as compared to 2009-10 due to weather, especially the rainfall. Higher WUE_I was recorded with MIS over CB during both the years. During 2009-10, highest WUE_I was observed in DS, MS being at par with it, while in 2010-11, significantly higher WUE_I was recorded with MS (Table 4). Increase in levels of N enhances the WUE_I and water use efficiency, however, the rate of increase was higher from 40 kg N /ha to 80 kg N/ha as compared to 80 to 120 kg N/ha during both the years. Wentworth and Jacobs, 2006 and Nazirbay et al., 2005 have also reported high water use efficiency and water saving under micro irrigation systems when practiced with fertigation of N. Interaction for irrigation systems and levels of N fertigation was found significant for WUE_I (Fig 2). With micro irrigation, water saving up to 50 per cent was possible through maintaining available soil moisture at low water tension during entire growth period (Patel et al., 2006). Irrigation scheduling in micro irrigation system provide water to the plants which matches the crop evapotranspiration and provide optimum irrigation at critical growth stages resulting in high water use efficiency (Wang et al., 2001; Kar et al., 2005; Turner, 1987; Kipkorir et al. 2002). The total soil moisture was measured *in situ* by gravimetric method during both the years at an interval of 2-5 days (Fig. 5). The soil moisture at field capacity (FC) and permanent wilting point (PWP) was 9.86 and 27.6 respectively based up on the soil texture. In CB, it reached maximim after two irrigations, followed by a phase which is approaching PWP. However, in MS and DS, the irrigation scheduling was done in such a way

Table 3. Yield attributes of mustard (cv: Rohini) as influenced by irrigation systems and N fertigation.

Treatments	Siliqua on main shoot		Total siliqua plant^{-1}		Seeds siliqua^{-1}		1000 seed weight (g)		Harvest Index	
	2009-10	2010-11	2009-10	2010-11	2009-10	2010-11	2009-10	2010-11	2009-10	2010-11
Irrigation systems										
CB	59.0^{a}	63.0^{a}	147.9^{a}	195.2^{a}	14.2^{b}	14.6^{a}	4.39^{a}	4.78^{a}	0.30^{c}	0.21^{a}
DS	63.2^{b}	73.4^{b}	192.4^{bc}	228.2^{ab}	14.2^{b}	15.4^{bc}	4.81^{b}	5.47^{bc}	0.22^{d}	0.22^{ab}
MS	59.5^{a}	73.6^{b}	207.8^{bc}	253.0^{bc}	15.4^{ab}	16.1^{d}	4.70^{b}	5.14^{c}	0.26^{ab}	0.24^{bc}
MS+CB	58.5^{a}	69.3^{b}	217.2^{c}	266.0^{c}	16.0^{a}	15.8^{cd}	4.59^{ab}	5.38^{bc}	0.33^{a}	0.26^{c}
DS+CB	63.6^{b}	61.6^{a}	165.6^{ab}	201.8^{a}	14.8^{ab}	15.1^{b}	4.69^{b}	4.99^{ab}	0.26^{bc}	0.25^{c}
Fertigation of N (kg ha^{-1})										
Control	56.2^{a}	51.8^{a}	106.6^{a}	162.6^{a}	13.2^{a}	13.7^{a}	4.50^{a}	4.97^{a}	0.27^{a}	0.22^{a}
40	62.0^{bc}	65.3^{b}	166.8^{b}	217.6^{b}	15.0^{ab}	14.9^{b}	4.60^{ab}	5.05^{a}	0.26^{a}	0.25^{b}
80	64.2^{c}	78.9^{c}	210.6^{c}	247.0^{c}	17.0^{c}	16.2^{c}	4.80^{b}	5.29^{a}	0.30^{b}	0.24^{b}
120	60.7^{b}	76.6^{c}	260.8^{d}	288.0^{d}	14.5^{a}	16.7^{c}	4.63^{ab}	5.29^{a}	0.27^{ab}	0.24^{b}

Note: Within column, value represents with different letter indicate significant difference ($P \leq 0.05$)

Table 4. Biological, seed, oil yield and assimilate supply of mustard (cv. Rohini) as influenced by irrigation systems and N fertigation.

Treatments	Biological yield kg ha^{-1}		Seed Yield kg ha^{-1}		Oil yield kg ha^{-1}		Assimilate supply (g siliqua^{-1})	
	2009-10	2010-11	2009-10	2010-11	2009-10	2010-11	2009-10	2010-11
Irrigation systems								
CB	4180^{a}	7618^{a}	1260^{a}	1759^{a}	550^{a}	716^{a}	0.25^{a}	0.29^{b}
DS	5100^{b}	8451^{b}	1590^{b}	1897^{ab}	731^{c}	779^{b}	0.29^{b}	0.30^{b}
MS	6510^{c}	8812^{c}	1660^{c}	2086^{b}	711^{c}	859^{c}	0.30^{b}	0.33^{c}
MS+CB	6850^{c}	8542^{b}	1680^{c}	2224^{c}	660^{bc}	902^{d}	0.29^{b}	0.30^{b}
DS+CB	5460^{b}	8374^{a}	1550^{b}	1914^{ab}	631^{b}	787^{b}	0.27^{a}	0.26^{a}
Fertigation of N (kg ha^{-1})								
Control	4770^{a}	6296^{a}	1220^{a}	1360^{a}	527^{a}	534^{a}	0.23^{a}	0.24^{a}
40	5500^{b}	7943^{b}	1390^{b}	1914^{b}	597^{b}	785^{b}	0.26^{b}	0.28^{b}
80	6020^{c}	9118^{c}	1680^{c}	2187^{c}	723^{c}	915^{c}	0.38^{c}	0.40^{c}
120	6210^{c}	10082^{d}	1780^{c}	2443^{d}	780^{c}	1000^{d}	0.28^{b}	0.31^{b}

Note: Within column, value represents with different letter indicate significant difference ($P \leq 0.05$)

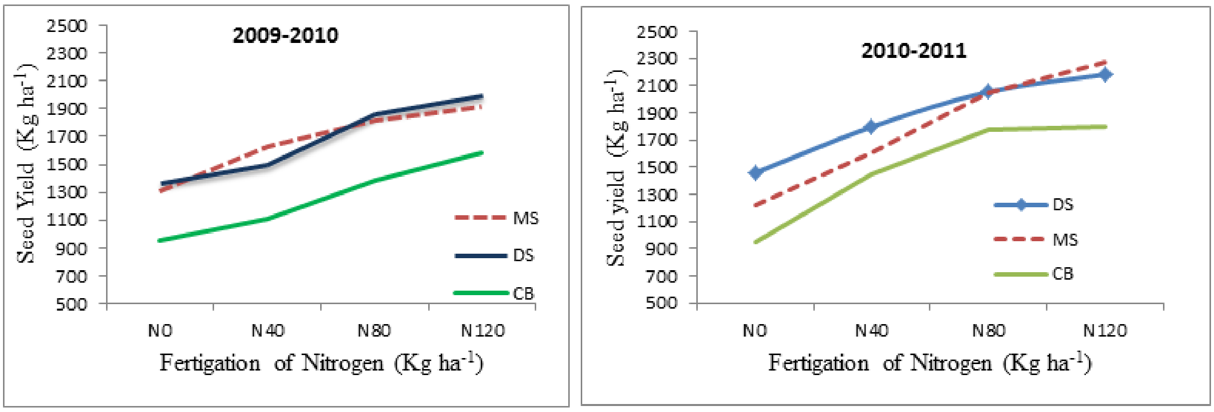

Fig 3. Interaction of seed yield and N fertigation of mustard under different irrigation systems during 2009-2010 and 2010-2011. The response of mustard to increasing N doses increased under MS and DS. Within a given N dose higher seed yield can be produced with MS and DS.

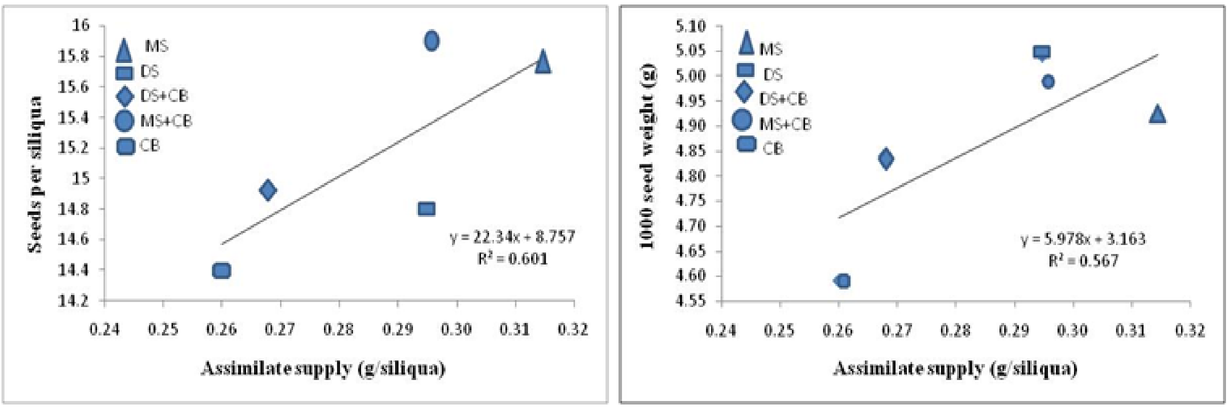

Fig 4. The relationship of assimilate supply with seeds per siliqua and 1000 seed weight of mustard indicating a higher biomass diversion for more number of bolder seeds under micro-irrigation in mustard (R^2 is the determination coeffecient).

that the plant seldom faced stress and the soil moisture remained higher as compared to CB. Although, the same quantity of water was applied in both MS and DS, the available soil moisture was lower in DS as compared to MS due to the configuration of the laterals. One lateral was laid among three rows of mustard and the soil moisture probably declined in the midle row. Water stress has a decisive role in influencing the growth pattern and yield of a crop through effects on nutrient uptake and internal hormonal status during sink development (Donald 1968) and almost every physiological process in the plant. Thus sink/seed development is the most critical stage in mustard for water stress. Jackson et al. (1981) introduced the theoretical method for calculating the crop water stress index (CWSI). The CWSI is a good indicator of plant response to available water and thus used to characterize plant water stress and schedule irrigation (O'Shaughnessy et al., 2012). The CWSI offers an independent and direct measure of crop water status that can easily be used to supplement soil water measurements and/or crop water balance modeling either with crop growth or ET models to improve irrigation scheduling. The CWSI was calculated for all irrigation systems at peak flowering. An inverse relationship was observed between the final seed yield and CWSI during both the years (Fig 4). The minimum CWSI was recorded for MS and MS+CB due to short intervals between two irrigations which developed favourable micro climate for plants.

Economics

The economics of the experiment was calculated in terms of the net returns, profitability and relative economic effeciency (REE). The highest net retuns were recorded in MS, DS and DS+CB being at par with it during the first year (Table 6). Likewise, the profitability was also obtained highest under MS. However, during 2010-11, the highest net returns were recorded in MS+CB. During the second year, MS, DS and DS+CB produced at par net returns and profitability due to intermittant rainfall in that season (Fig. 1). These rains nullify the impact of non-uniform application of water through drip system due to the lateral configuration (1 lateral among 3 mustard rows; 1:3). Also, these higher rains promoted growth under higher N doses and the efficient utilization of N through wider canopy development in mustard improved yield, making 120 kg ha^{-1} N more profitable than 80 kg ha^{-1} during the second year. Nitrogen availability in soil, its uptake and utilization in plants are very closely associated with the soil moisture. The yield increment due to N application thus depends up on the available moisture in the

Table 5. Production efficiency, sustainable yield index and irrigation water use efficiency of mustard (cv. Rohini) as influenced by irrigation systems and N fertigation.

Treatments	Production efficiency (kg ha^{-1}day^{-1})		Sustainable yield index		Irrigation water use efficiency (kg ha^{-1}-mm)		Water Use Efficiency (μmoles mmoles^{-1})	
	2009-10	2010-11	2009-10	2010-11	2009-10	2010-11	2009-10	2010-11
Irrigation systems								
CB	8.1[a]	11.3[a]	0.45	0.46	10.5[a]	14.9[e]	0.43	0.48
DS	11.0[c]	12.2[ab]	0.64	0.51	28.0[c]	31.6[b]	0.42	0.47
MS	11.0[c]	13.5[b]	0.63	0.58	27.7[c]	34.8[a]	0.46	0.51
MS+CB	10.0[bc]	14.4[c]	0.57	0.63	19.1[b]	24.7[c]	0.44	0.49
DS+CB	9.6[b]	12.4[ab]	0.53	0.52	18.2[b]	21.3[d]	0.48	0.54
Fertigation of N (kg ha^{-1})								
Control	8.5[a]	9.3[a]	0.43	0.32	16.7[a]	17.8[a]	0.42	0.49
40	9.2[a]	12.3[b]	0.50	0.52	19.0[b]	24.3[b]	0.42	0.48
80	11.4[b]	14.0[c]	0.68	0.61	23.1[c]	28.0[c]	0.44	0.49
120	10.8[b]	15.5[d]	0.64	0.71	24.0[c]	31.6[d]	0.49	0.53

Note: Within column, value represents with different letter indicate significant difference (P≤0.05)

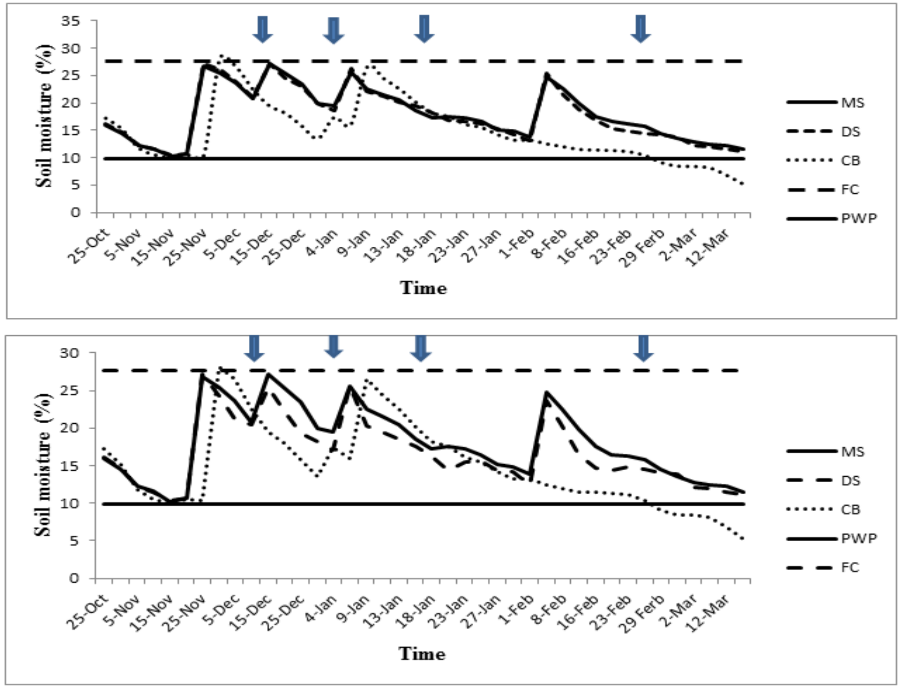

Fig 5. The variation in available soil moisture (%) with time under various irrigation systems during 2009-10 and 2010-2011. The down arrows indicates the four irigation scheduling for MS and DS. The soil moisture between FC and PWP indicates the available soil moisture.

soil, its retention capacity and its distribution across the crop growth stages. Enhanced water availability increases seed and root N along with the N harvest index, consequently the yield is greater under high-moisture availability in MS and DS (Gan et al., 2010). The pattern of plant N accumulation, mineralization and utilization in plants are influenced by water availability and uptake (Campbell et al., 2008). Hence, optimum moisture availability improved seed yield of mustard under high N doses during the second year through N metabolism and N redistribution in plants. The optimum turgor under micro-irrigation system bring hormonal status to suitable concentration and restrict flowering and pod abortion. It also increases photo-assimilation and sink strength (Mir et al., 2009).

The REE indicates the profitability enhacement with reference to control treatments. In case of irrigation methods, MS and MS+CB were found more economic, keeping CB (farmers practise) as control in 2009-10 and 2010-11 respectively. Likewise, REE in was maximum with 80 kg N ha^{-1} in the first year, while during the next year the crop responded up to 120 kg N ha^{-1} due to higher rainfall and favourable climatic conditions. Likewise, the B:C ratio obtained under all the MIS was significantly higher than CB. Highest B:C ratio was recorded with MS, followed by MS+CB during 2009-10. During 2010-11, it was highest under MS+CB, followed by MS alone. During 2009-10, highest B:C ratio was obtained with 80 kg N ha^{-1}, however, during 2010-11, the response of mustard to applied N was observed up to 120 kg N ha^{-1}. The higher yield obtained under micro-irrigation systems and increasing N doses resulted in higher B:C ratio.

Materials and Methods

The experiment

An experiment on micro-irrigation systems and fertigation in Indian mustard under semiarid conditions was conducted at the research farm of Directorate of Rapeseed Mustard Research, Bharatpur, India, located at 77.30^0 E longitudes, 27.15^0 N latitude and 178.37 meter of altitude. The average climatic status remained consistent throughout the experimentation except rainfall. The significant fluctuation in rainfall intensity and distribution is attributed to the winter rains of rainfed subtropical region of the subcontinent. The total rainfall received during 2010-11 was higher with relatively uniform distribution as compared to 2009-10, which influenced mustard growth and productivity during both the years. Indian mustard is reported to tolerate annual precipitation of 500 to 4200 mm and the annual temperature ranging from 6 to 27°C. Minimum and maximum temperature decreases from October to January and again starts rising from February–March. The maximum and minimum relative humidity ranged between 77-98 % and 23-74% respectively during the crop season. The soil of the experimental field was clay loam (25% sand, 41% silt and 34% clay) with the pH range of 8.5-9.5, 2.5-3.5 dSm^{-1} EC, 2.6 gkg^{-1} organic carbon, 125 kg $KMnO_4$ oxidizable Nha^{-1}, 19.5 kg 0.5N $NaHCO_3$ extractable Pha^{-1} and 245 kg 1.0N NH_4OAc exchangeable Kha^{-1}. The initial bulk density and infiltration rate of the soil was 1.50 Mg $(m^3)^{-1}$ and 5.9 mm hr^{-1} respectively. The experiment was undertaken during winter seasons of 2009-10 and 2010-11 in spilt plot design (SPD) with three replications. The treatments consisted of five irrigation systems in main plot *viz.* micro-sprinkler system (MS), micro sprinkler combination with check basin (MS+CB), drip irrigation system (DS), drip irrigation combination with check basin (DS+CB) and check basin (CB) alone. In subplot, four treatments of N fertigation *viz.* Control (0 N), 40, 80 and 120 kg N ha^{-1}were taken.

Crop husbandry

The experiments were conducted under *Sesbania* green manure-Indian mustard cropping system. Indian mustard variety Rohini was chosen from the most productive and best adapted cultivars to this type of semi arid conditions. The duration of the variety was 140-150 days, which was sown on 20 and 25th October and harvested on 10th and 12th March during 2009-10 and 2010-11 respectively. The sowing bed was prepared by plowing to a depth of 0.25 m, which was followed by surface cultivation. The seeds were sown @ of 5 kg/ha at 30x 10 cm spacing at a depth of 5 cm with the help of seed drill. The plant-to-plant distance was maintained at 10-15 cm by thinning at 25 DAS. Nitrogenous and phosphorous fertilizers were applied as urea, di-ammonium phosphate (DAP) and murate of potash (MOP). The whole DAP and MOP were applied at the time of land preparation. Mustard was harvested manually by cutting 5 cm above the ground using sickles. The yield attributes and yield observations were recorded at maturity of the crop. Observations on yield attributes were recorded by selecting five random plants from each plot. The border of 0.60 metre was left to record the seed yield per plot and it was extrapolated to calculate per hectare seed yield.

Irrigation management

The check basin method is the usual practice among the farmers in India, particularly in Rajasthan. Two irrigations were provided though check basin one at 35-40 days and another at 65-70 days after sowing, coinciding the critical stages of growth in mustard. During irrigation, 60 and 20 mm water was applied in check basin and micro-irrigation system receptively. The micro irrigation systems *viz.* MS and DS are portable. Hence, irrigation scheduling can be done as, first irrigation through CB, followed by micro irrigation through MS or DS as per the water requirement of the crop. Under micro-irrigation, irrigation was scheduled on the basis of water requirement and soil moisture balance. The micro-sprinkler head operated at 2.5 kg/cm^2 pressure and each micro sprinkler head covered the diameter of 9 meters. The pressurized irrigation systems were operated through a shallow tube well with 5 HP motor. These heads were installed to cover the field in an overlapping manner. The uniformity co-efficient of the entire micro-irrigation system was above 85 %, to ensure even water application in the field. The micro sprinkler irrigation system was operated based on water requirement and soil moisture storage. The volume of water to be given was calculated as per FAO Irrigation Water Management Training Manual No. 3 (Brouwer and Heibloem, 1986). The gravimetric soil moisture status was monitored throughout the cropping season. It was determined ([g wet soil—g dry soil] x [g dry soil]−1) by collecting soil samples from 0–5 cm with a sharply edged soil corer, weighed and oven dried for two days at 105º C.

Physiological parameters

Photosynthesis and gas exchanges activities of mustard were measured using a portable photosynthesis system (Model LI-6400, LICOR, inc. Lincoln, Nebraska USA) during 1000-

Table 6. Net return, profitability and relative economic efficiency of mustard (cv.Rohini) as influenced by irrigation systems and N fertigation.

Treatments	Net returns ($\$ha^{-1}$)		Profitability ($\$ha^{-1}day^{-1}$)		Relative economic efficiency (%)		B:C ratio	
	2009-10	2010-11	2009-10	2010-11	2009-10	2010-11	2009-10	2010-11
Irrigation systems								
CB	389.3[a]	589.5[a]	2.53[a]	3.83[a]	-	-	2.50	2.05
DS	565.2[b]	667.6[b]	3.67[b]	4.34[b]	45.2	13.3	3.70	2.63
MS	572.3[b]	716.1[b]	3.72[b]	4.6[5b]	47.1	21.5	3.65	2.80
MS+CB	505.3[bc]	783.2[c]	3.28[bc]	5.08[c]	29.8	32.8	3.28	3.08
DS+CB	473.2[b]	646.8[b]	3.07[c]	4.20[b]	21.6	3.07	3.05	2.55
Fertigation of N (kg ha^{-1})								
Control	391.3[a]	401.6[b]	2.54[a]	2.61[a]	-	-	2.48	1.52
40	451.4[b]	571.1[a]	2.93[a]	3.71[b]	15.3	42.2	2.90	2.58
80	627.7[d]	640.2[c]	4.08[c]	4.16[bc]	60.4	59.4	3.94	3.02
120	592.3[c]	710.6[d]	3.85[b]	4.61[c]	51.4	76.8	3.62	3.36

Note: Within column, value represents with different letter indicate significant difference (P≤0.05).

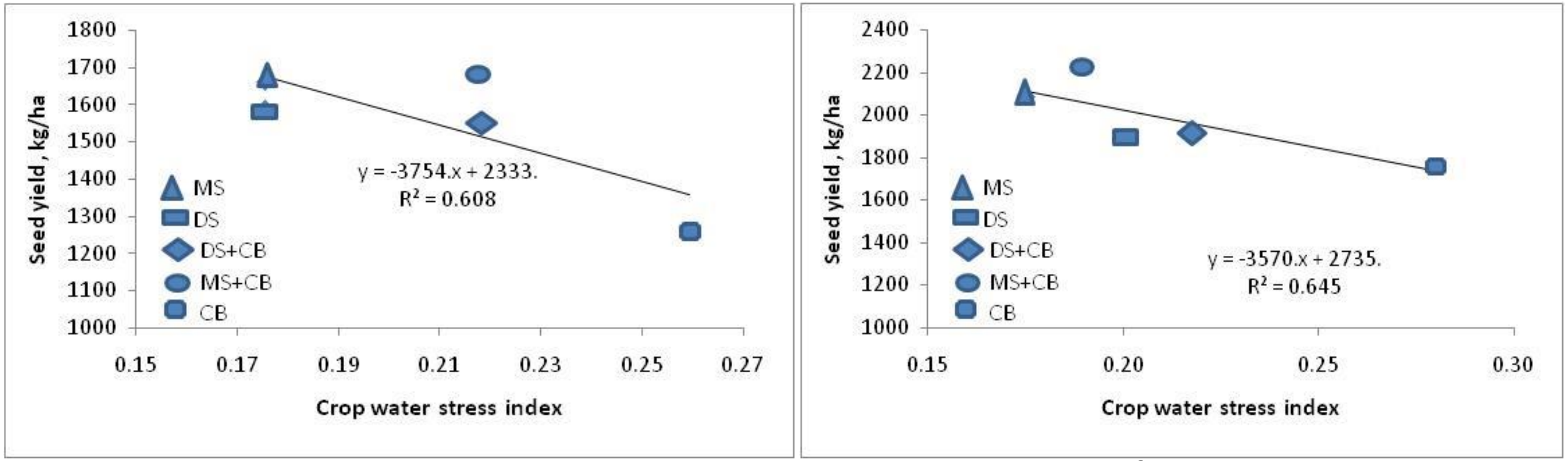

Fig 6. The inverse relationship between seed yield and CWSI at peak flowering during 2009-10 and 2010-11 (R^2 is the determination coefficient).

1300 hours under clear sunshine conditions at 40 and 80 days after sowing and pooled data presented every year in the tables. The fully expanded leaves on two-third above part of plants were selected randomly in each experiment. The portable measuring system can simultaneously determine the net rate of photosynthesis (Pn), stomatal conductance (Gs), intercellular CO_2 concentration (Ci) and transpiration rate (E).

SPAD devolved by soil-plant analysis and development unit of Minolta Company (SPAD 502) was used to record relative leaf chlorophyll. The observations on SPAD chlorophyll meter in two different mustard growth stages (50 and 75 DAS) were recorded. The youngest fully expanded leaf of 3 plants in 60 plots was used for SPAD measurement. Triplicate readings were taken on one side of the midrib of each single leaf blade, midway between the leaf base and tip and then averaged.

Assimilate supply

It is the capacity of the crop to maintain both seed number per pod and total number of pods being related to the dry weight of the crop at peak flowering (Mendham et al., 1984). It is calculated as:

$$AS = AGDM/n \quad (1)$$

Where, AS is the assimilate supply in g per siliqua, AGDM is the above ground dry matter of individual plant at peak flowering (at 90 days after sowing) and n is the number of siliquae of that individual plant.

Production efficiency

Production efficiency (PE) represents the increase in seed yield on a daily basis (Tomar and Tiwari, 1990). It can be calculated by the following mathematical equation:

$$PE = SYe/\Delta n \quad (2)$$

Where, PE is the production efficiency in kgha^{-1}day^{-1}, SYe is the economic yield in kg ha^{-1}, Δn is the duration of the crop. Higher PE indicates a larger translocation capacity of the source towards the sink.

Sustainable yield index

Minimum assured seed yield as compared to maximum observed yield of mustard over the years was quantified through sustainability yield index (SYI). The SYI is a measure of the sustainability of a cropping system. It can be calculated by the following mathematical equation:

$$SYI = (Ya - \sigma)/Ym \quad (3)$$

Where, Y_a is mean yield, σ is the standard deviation of yield, and Y_m is the maximum yield obtained under a set of management practices (Singh et al., 1990).

Irrigation water use efficiency and water use efficiency

The irrigation water use efficiency (WUE_I) was calculated as:

$$WUEi = SYe/Wi \quad (4)$$

Where, WUEi is the irrigation water use efficiency in kg ha^{-1}mm^{-1}, SYe is the economic yield and Wi is the water applied through irrigation.

The water use efficiency (WUE) at the plant level is a more accurate reflection of assimilate accumulation per unit of water utilized (Song-Heng et al., 2004). It can be calculated as:

$$WUE = Pn/E \quad (5)$$

Where, Pn is the rate of photosynthesis and E is the evapo-transpiration, it is expressed in µmoles/ mmoles.

Net returns, profitability and relative economic efficiency

The net returns per hectare are calculated by deducting the cost of cultivation from the gross returns. The profitability of various irrigation systems and N fertigation was also calculated to find out per day return. It reflects the monetary advantage on a daily basis for growing mustard. It can be compared with other enterprises and help the farmers in decision making with the given set of resources. Profitability can be calculated as:

$$P = NR/D \quad (6)$$

Where, P is the profitability in US dollars ha^{-1} day^{-1} and D is the duration of the crop.

The comparative advantage from the adoption of micro irrigation and N fertigation can be represented through relative economic efficiency (REE), expressed in percentage (Prasad et al., 2011). The (REE) of the various treatments was calculated by using the following formula:

$$REE = \Delta N/A * 100 \quad (7)$$

Where, Δ N is the difference in the net returns from the micro irrigation systems and check basin for main plots and the difference in net returns from control to N fertigation for sub-plots, A is the net returns from CB for main plots and the net returns from control treatment for sub-plots.

Statistical analysis

The data were statistically analyzed using Fisher's analysis of variance technique (Steel et al., 1997) and the treatments means were compared by Duncan's Multiple Range (DMR) test at level of 0.05 probabilities. The standard analysis of variance (ANOVA) test was performed using SPSS 17.0 statistical software to compare the treatment means for each year separately.

Conclusion

Indian mustard (*Brassica juncea)* is an important edible oilseed crop in Indian subcontinent and also in other tropical and subtropical regions. It is mainly grown under limited water availability conditions but is highly responsive for irrigation. The limited available water in semi-arid areas can be efficiently utilized through proper irrigation scheduling under micro irrigation. The application of major elements, especially N through fertigation has become practical. The response of the mustard for the applied N can also be enhanced through micro irrigation systems. Nitrogen dose at 120 kg ha^{-1} became profitable with both MS and DS. The efficiency of irrigation water can be improved by more than 50%, apart from the fact that the favorable water regime under micro irrigation improves physiological parameters, growth, yield attributes and yield of Indian mustard. This ultimately results in higher profits through enhanced seed and oil yield.

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