Influence of Drip Irrigation and Mulch on Leaf Area Maximization, Water Use Efficiency and Yield of Potato (*Solanum tuberosum* L.)

Santosh Kumari Division of Plant Physiology Indian Agricultural Research Institute, New Delhi 110012, India Tel: 91-6542-4724 E-mail: smile.santosh.kumari@gmail.com

Received: April 1, 2011	Accepted: April 14, 2011	Online Published: December 1, 2011
doi:10.5539/jas.v4n1p71	URL: http://dx.doi.org	g/10.5539/jas.v4n1p71

Abstract

This study critically assessed the influence of frequent availability of water i. e. drip irrigation and mulch on optimum leaf area development of potato that control light interception and soil moisture conservation. Crop growth was stimulated in terms of early pick up of leaf areas that quickly covered the ground and improved transpiration efficiency. Drip irrigation increased water use efficiency three times as compared with furrow irrigation (conventional method of irrigation). Black Polyethylene mulch (25µm) conserved soil moisture, raised soil temperature by 9°C, stimulated shoot, solon and root growth, increased the total tuber number and yield but reduced the grade of tubers. Drip irrigation may prove a viable tool for source-sink alteration; stimulating early stolon initiation combined with ability to quick ground cover and sustained leaf growth for new tuber initiation for seed production as well as extended tuber bulking of early formed tubers for obtaining maximum yield with 50% saving of irrigation water and efficient use of nitrogen fertilizer.

Keywords: Potato, Drip irrigation, Mulch, Leaf area, Water use, Tuber grade, Yield

1. Introduction

Water is the key input in potato production and the problem of water management vary from region to region. India occupies a unique position where potato can be grown throughout the year in different parts of the country. About 81% of the potato is grown in plains during winter under short day conditions; 13% in the hills during summer under long day and about 6% in the plateau during the rainy season under almost equinox conditions. The winter crop is invariably irrigated but the summer and the rainy season crops are exposed to drought and excess of water at different stages of growth (Grewal and Singh 1974). In India, potato is generally grown when maximum day temperature is below 35^oC and night temperature not more than 20^oC. Optimum temperature for potato growth ranges from 15 to 25^oC. Temperature below 21^oC favors tuberization. High-frequency water management by drip irrigation minimizes soil as a storage reservoir for water, provides at least daily requirements of water to a portion of the root zone of each plant, and maintains a high soil matric potential in the rhizosphere to reduce plant water stress (Phene and Sanders, 1976). Many studies have shown drip irrigation to be well suited for row crop and potato production (Sammis 1980; Shalhevet et al. 1983). Optimizing irrigation efficiency, through properly designed, maintained, and managed irrigation system, to derive the maximum crop yield from every increment of water available will generally lead to greater economic return than any other change in management (King et al. 2003).

Potatoes have a shallow root zone and a lower tolerance for water stress than most other crops (Hang and Miller 1986). Water stress causes reduction of yield by reducing growth of crop canopy and biomass. The extent to which tuber yield and quality are adversely affected by drought will depend upon the severity, timing, and duration of water stress during the growing season. It is critical to have an understanding of how water stress at each growth stage influences tuber yield and quality if a grower is to balance water supply with potential returns. The amount of water needed by potatoes varies with soil type, temperature, humidity, air movement, plant and stem populations, varieties and cultural practices (Wiersema 1987). Low or fluctuating moisture levels can contribute to common scab, early dying, hollow heart, knobby tubers, low dry matter; low tuber set, and low yield. Excessive soil moisture resulting in poor aeration and water logging of the soil reduces the yield and in extreme cases causes tuber rot, and enlarged lenticels. The enlarged openings of epidermis detract potato from

their appearance and allow entry of disease organisms, causing tuber rot in storage (Davis et al. 1974; Adams and Lapwood 1978; Kleinschmidt and Thornton 1991). The preference for producing this drought sensitive crop in coarse textured soils with limited water holding capacities makes precise irrigation management a necessity to obtain optimum yield and quality (Marutani and Cruz 1989; Tomasiewicz et al. 2003). Fertigation ensures substantial saving in fertilizer usage and reduces leaching losses (Hebber et al. 2004). Furrow irrigation is wasteful because interrow location is characterized by high leaching and low water uptake rates by plant roots. As the plant looses its erect stature, stem flow is reduced and the combination of splash and runoff from the hill sides contribute to increased infiltration in the furrow (interrow) and subsequent leaching of water and nitrogen (Saffigna et al. 1977). The beneficial effects of different mulches (both organic and synthetic) on growth and yield of different vegetables have been reported by earlier investigators (Asiegha 1991; Shrivastava et al. 1994). Therefore, the aim of this study is to understand the leaf area development, water use efficiency and yield responses of potato crop to the frequent availability of water (drip) and mulch (further moisture conservation and changed soil temperature) using black polyethane.

2. Material and Methods

2.1 Sites and seasons

The experiments were carried out between November 1999 and March 2000 under late sown winter conditions in the field of Water Technology Centre, at Indian Agricultural Research Institute, New Delhi, India. The fields were characterized by a sandy loam soil (Typic Ustochrepts), with mean water contents between 25% and 4.5% by weight at field capacity (-0.02 MPa) and permanent wilting point (-1.5 MPa), respectively. The water table is at a depth lower than four meter and therefore, the contribution of ground water was assumed to be insignificant. The available water measured gravimetrically was 20 cm down to a depth of 150 cm at the time of crop sowing. Total rainfall during growing period was 41.40 mm. The soil of the experimental area was deep, well-drained sandy loam comprising 54% sand, 31% silt and 15% clay (Rajput and Patel 2006). The bulk density of soil was 1.47 g cm^{-3} , field capacity 0.25 and saturated hydraulic conductivity 1.17 cm h⁻¹, respectively.

2.2 Plant material and experimental details

Potato tuber seeds from true potato seed (TPS) were planted on ridges of 30 cm height at 10 cm depth after preparation of field, in complete randomized block design with three replications. The plot size was 5 m x 5 m and the furrow irrigated plots were separated by two meters from alternate furrow irrigated plots. Plant to plant distance was 30 cm and row to row distance was 60 cm. Basal dose of fertilizer was applied in the form of urea, single superphosphate and muriate of potash in furrow and alternate furrow irrigation treatments only at the rate of 120:60:60 (NPK). Irrigation treatments were started a week after sprouting. Liquid fertilizer (12: 6: 6) application was followed by irrigation every third day to avoid clogging of the drippers. Level furrows were created between rows to ensure uniform water distribution in plots irrigated by furrow. Furrows were closed at the end to prevent runoff and a flow meter was used to measure the amount of water applied. The depth of water applied (average of seven irrigations) in furrow and alternate furrow irrigation was 46.55 mm and 40 mm, respectively after every fortnight. Total amount of water supplied through drip, alternate furrow and furrow irrigation was 133.76 mm, 282.40 mm and 325.80 mm as depth of water; respectively, during crop duration started from fifteen days after sowing. Drip irrigation was performed through laterals of 16 mm diameter per row and pressure-compensating emitters (4 L h^{-1} flow) placed at 50 cm distance in the furrow in between two plants. The amount of water depleted by evapotranspiration was replenished by controlling the time of operation of drip irrigation system. The values of statistical uniformity and water distribution uniformity were more than 92% during the cropping season. Potato roots had spread up to a radius of 25 cm from the dripper discharge point and most were contained within 30-40 cm width and 25 cm depth. Minimum and maximum water replenished was 2 mm and 5.50 mm depth of water, respectively in 30 irrigations through surface drip irrigation system.

Quantity of water replenished was calculated based on cumulative pan evaporation (CPE) during the irrigation application days. The CPE was corrected by pan factors and crop factor. Reference crop evapotranspiration was calculated on a daily basis by using Penman–Monteith's semi-empirical formula (Smith et al. 1991). The necessary weather data (temperature, relative humidity and rainfall) were collected from an automatic weather station, 30 m away from the field site. The mean of maximum and minimum temperatures ranged between 22.3-29.6° C and 7-13° C, respectively during crop season (November to March). Polyethylene black mulch of 25 micrometer (μ m) was used to avoid weed growth and for conservation of water on the ridges (20 cm wide strip to cover both sides of the furrow) for entire season from the date of sowing. Plants with two stems (Wiersema 1987) were used for recording leaf area (leaf area meter Li-3100), stolon number, stolon dry weight, yield components and total tuber yield analysis per plant and three replicates representing the treatment

population at 15 days interval starting from 25 days to 80 days after sowing. Yield data from final harvest of one square meter were used for calculating water use efficiency and number of tubers in different grades by weight. Volumetric soil water content in relation to irrigation, plant uptake, and yield and replicated plots was studied to evaluate all water management options. Measurements of volumetric soil water content using a hammer driven probe were used to calculate the cumulative water use by the crop at the time of harvest in replicated plots. This cumulative water use was used for calculating water use efficiency of potato crop under different treatments.

Statistical analysis of data was done using Analysis of Variance (ANOVA) using MStat computer software.

The different irrigation treatments are abbreviated as Furrow (F), Furrow with mulch (FM), Alternate Furrow (AF), Alternate Furrow with mulch (AFM), Drip (D), Drip with mulch (DM) in presenting results of this study.

3. Results and Discussion

3.1 Water use and yield of potato

Yields were significantly greater under drip irrigation (24.95 t/ha) and drip irrigation combined with mulch (26.02 t/ha) than furrow, furrow + mulch, alternate furrow and alternate furrow + mulch (Table 1). Cumulative water use was reduced under drip irrigation due to reduced losses and increased application frequency of water. Further moisture losses were reduced when mulch was used to cover the field under alternate furrow and drip irrigation. The tuber yield was higher in furrow irrigation as compared to alternate furrow irrigation; however, additional use of mulch was not beneficial both in terms of cost of production and increase in yield by conserving moisture in both the treatments. The cumulative effect of repeated mild water stress at individual stages in case of alternate furrow irrigation (17% water saved) was 2.4 t/ha (18% yield reduction) reduction on total tuber yields under furrow irrigation. Restriction on leaf area expansion and stomatal conductance by reduced water contents and induced abscisic acid signal might have contributed to reduced water use (Liu et al. 2006). Number of all grades of tubers increased and weights of large and medium sized tuber were improved under drip irrigation (Fig. 1). The use of small seed tubers (1-5g) is an important aspect of field multiplication, instead of cut seed pieces that may result in further economies in production costs using drip irrigation system and reduction in disease in seed tubers (Struik et al. 1989; Allen et al. 1992; Ewing and Struik 1992; Caldiz 1996). Potato and other vegetable crops are commonly priced differently across a range of product sizes. Marketable yield and gross income were compromised largely by medium and small tuber yield by use of mulch combined with furrow and drip irrigation system when compared with drip irrigated plants. However, Drip irrigation + mulch produced the highest number of seed tubers (Fig. 1).

3.2 Leaf area and water use efficiency

The present study demonstrated that total leaf area achieved was higher (Table 2) under drip with less cumulative water use by the crop and ground cover was the fastest among alternate furrow and furrow treatments. The transpiration efficiency was improved markedly in terms of total tuber yields with less cumulative water use in this study, in conformity with Erdem et al. (2006). However, nitrogenous fertilizer was utilized more efficiently to develop leaves with optimum size (full leaf size) with more frequent availability of water. Nitrogen improved water use efficiency tremendously by increasing leaf area expansion, number of palisade cells, chloroplast development and total protein contents in sunflower leaves (Kumari and Dixit 2004). Quantitatively, transpiration and evaporation are the major components of water used by the crop plants. In potato, transpiration ratio is reported to be 544 as compared with almost similar values in wheat grown in the same season (Singh 1974). However, potato has a higher harvest index and therefore, a more efficient user of water than wheat. Still, transpiration losses are considerable and have to be reckoned with. The field under potato, if irrigated frequently, is subjected to high rates of evaporations; especially in the periods before vegetation has covered the ground fully. It was desirable to reduce evaporation by the use of mulches as far as possible. When the plant is unable to meet the evaporative demands of the atmosphere, the leaves lose turgor. Consequently, stomata close which restricts both photosynthesis and water loss. In alternate furrow irrigation, higher evaporative losses developed mild water stress in the crop and leaf area (thick leaves) development was slow as compared to drip and furrow irrigations. Total fresh tuber yield from drought crops tended to decline with increasing fertilizer up to 80 kg/ha (Ferreira and Gonçalves 2007) due to inability of plants to take up and utilize nitrogen. The yield increases with higher total available soil nitrogen under deficit irrigation, but the yield response diminishes as the amount of total seasonal water decreases (Ojala et al. 1990). Increase in dry matter yields require the interception of more radiation, which inevitably means increased water demand (Beukema and Zang 1990). A drip irrigation system can easily be used for fertigation, through which crop nutrient requirements can be met accurately (Or and Coelho 1996; Ferreira and Carr 2002). Potato nitrogen need has to be closely synchronized with specific growth stages i.e. sprouting development, vegetative growth, tuber initiation, tuber bulking and maturation. Sufficient

nitrogen is needed in the initial stages to stimulate leaf growth, but excess nitrogen applied early can cause excessive vegetative growth which may delay tuber initiation (Ritter et al. 2001).

Water use efficiency of potato was increased three times under frequent availability of water compared with traditional system of furrow irrigation. Saturation of the soil profile for more than 8-12 hours under furrow irrigation can cause root damage due to lack of oxygen required for normal respiration. Surface drip system placed in the furrow delivers water directly to the soil zone where uptake is the highest, that system would be expected to have the lowest water use requirement. Black Polyethylene mulch further improved the water use efficiency (4.5 times) by reducing the evapotranspiration as well as increasing the total tuber yield but reduced the marketable tubers. An increase in soil temperature by 9°C under black Polyethylene mulch (Wang et al. 2009) stimulated shoot growth, stolon growth and subsequently resulted in tuber formation of reduced weight. Several studies have demonstrated that increased temperatures not only increase partitioning into shoots (Menzel 1985; Wheeler et al. 1986; Wolf et al. 1991; Timlin et al. 2006), but also increase partitioning into combined stolons and roots (Wolf et al. 1991). Growth was stimulated in drip to the extent to push up the yields by increasing tuber number and mean weight of the tubers (Fig.1) with little increase in transpiration and by reducing the grade and increasing total number of tubers in drip + mulch treatment. Leaf area development of potato crop under furrow and drip irrigation in combination with mulch was in excess as compared to drip irrigation at all stages of growth and development (Table 2). Therefore, responses of plant to mulch cover need further work at different stages of growth and development.

3.3 Leaf area duration in relation to tuber initiation and dry matter partitioning

Total leaf areas were higher with frequent irrigations 1628, 4529 and 4275 cm² (Table 2) when compared with conventional methods of irrigation. These consistently higher values of leaf area between 25 days to 60 days after sowing were related to early initiation of stolon, total number and dry weight of stolons (Fig. 2 and 3). However, four stolons (2-3cm) were observed at 22 days and the ground was covered by leaf area under drip treatment at 25 days after sowing. Stolons developed in all other treatments at 25 days after sowing. The early initiation of stolon and tuber was important instead of length and total number of stolons. Early stolon formation and tuber initiation established sink strength that led to improved partitioning of photosynthets to economic yields in the crop under drip irrigation. Leaf area expansion was reduced and stabilized during 40 to 80 days after sowing. The crop growth stage was reflected in leaf area reduction due to senescence at tuber bulking stage (60-80 days) while net photosynthesis and dry matter production depends on the amount of radiant energy intercepted by larger leaf canopy (Table 2). Crop matured earlier under drip and all irrigation treatments accompanied with mulch than furrow and alternate furrow irrigations. Crop growth in terms of leaf area development was slow and leaves were thicker under alternate furrow and extended till 80 days after sowing. Leaf area duration was probably the most important feature of the foliage besides net photosynthetic rate (Baker and Moorby 1969). A well-maintained leaf area index of about 3.0 to 5.0 provides maximum photosynthetically active surface area and results in rapid tuber bulking. A delay of tuberization has been observed in aeroponic cultures where the stolon environment did not provide mechanical stress (Lugt et al. 1964). Moreover, the increased stolon length achieved in microclimates under mulch treatments supports this hypothesis. Any improvement in light interception achieved by an increased availability of nitrogen by drip irrigation were counterbalanced by unfavorable partitioning of assimilates in long and thick stolons (contributed in dry weight of stolons), plant height and leaf area expansion in drip and furrow irrigation with mulch treatment. Use of mulch in all irrigation treatments stimulated stolon length and leaf area expansion (Table 2). This response to the wet regime could partly be attributed to moderating effect of soil moisture on soil temperature (Singh et al. 1935; Struik et al. 1989). This study clearly showed that reduced leaf area resulted in reduction of yield (Jefferies and Mackerron 1989) in potato crop due to irrigation in alternate furrows.

Tuber initiation needs the cessation of stolon growth, which is linked to ethylene synthesis (Vreugdenhil and Struik, 1989) and tuber number positively correlates with leaf area and number of young leaves (Kahn et al. 1983). New emerging leaves under drip irrigation help in continuous initiation of tubers, and later formed tubers develop only to the weight of 3-4g due to a limited supply of photosynthets by smaller leaves due to onset of flowering. Drip irrigation thus proved to be an alternate mean for source sink alteration as achieved by plant growth regulators. Total tuber number and the tuber number in different categories by size were also reflected in tuber yield, possibly as a consequence of a great sink capacity in drip irrigated plants. The presence and growth rate of sink (Moorby 1970; Gutam et al. 2005) affected assimilate production and translocation as reflected in dry weight of stolon at 60 days after sowing in different irrigation treatments. The earlier onset of leaf senescence under drip irrigation (Table 2) and crop harvesting generally will permit the operation to be completed in better

soil temperature (no soil compaction) and tuber moisture conditions with less tuber damage and less loss during storage as suggested by King et al (2003).

3.4 Plant response to water stress

Studies on the response of potato to water stress conclude that even moderate water deficits can result in a low above ground biomass, tuber yield and tuber grade (Hang and Miller 1986; Kashyap and Panda 2003; Steyn et al. 2007). Water stress during the vegetative growth stage reduces leaf area, vine and root expansion, plant height, and delays canopy development. Reduced vine and leaf growth limits the photosynthetic capacity (Anita and Mauromicale 2006) on the other hand the reduced root development limits the plant's ability for water and nutrients uptake. Water stress during tuber initiation can substantially reduce tuber yield and guality while stress later during tuber bulking can cause dark stem-end fry color and reduced specific gravity (Eldredge et al. 1996). Although additional tubers may continue to form on stolons during later stages of plant development, tubers that contribute the most to marketable yield are formed at tuberization stage. MacKerron and Jefferies (1986) have shown that increased duration of water stress before tuber initiation reduces tuber set per stem. Sustained irrigation deficits during the tuber bulking will reduce tuber size and marketable yields. The presence of tubers may modify the response of net photosynthesis to water stress possibly through regulating the leaf carbohydrate level and thereby mitigate the adverse effect of water stress on photosynthesis (Basu et al. 1999). Water stress interrupts new leaf formation (Munns and Craig 1974) and expansion of thick leaf to full size (Santosh Kumari 2010) and result in loss of tuber set and tuber bulking. Water deficits reduce plant growth by reducing the internal water pressure in plant cells (turgor pressure), which is necessary for cell expansion. The crop in the alternate furrow treatment was accessing water from a smaller volume of soil than the furrow irrigation. Hence, the same rate of water uptake (and growth rate) by the crop in the alternate furrow treatment could not be maintained as the crop was required to extract water at higher suctions than the furrow irrigated crop. The crop grown with alternate furrow did not receive the water that fulfilled its requirements which resulted in significant reduction of leaf area per plant in potato crop between 60 to 80 days after sowing under alternate furrow irrigation. Under furrow and sprinkler systems, reductions in water applications for potato below full replacement of crop evapotranspiration, when silt loam soil is allowed to become drier than 60 kPa, result in yield reduction and loss of economic return (Shock et al., 1998a). There are quite large diurnal changes in the water contents of the tubers caused by changes in the transpirational demand for water (Baker and Moorby 1969). Whereas frequent availability of water helps in maintaining uniformity of tuber cells through out the bulking period. Therefore, the ratio of starch/ water and quality of tubers might remain unchanged. Drip treatment maintained a large photosynthetically active leaf surface area that is necessary to maintain high tuber bulking rates for extended periods. Alternately, maintenance of this large active leaf surface area requires continued development of new leaves to replace older, less efficient ones. Mulching conserved moisture and stimulated the shoot and root growth (40-80 days) and mobilization of photosynthets was reflected in an increase in the number of medium sized tubers especially in alternate furrow irrigation.

The yield advantage of adopting the drip irrigation system over furrow irrigation can be in terms of 50 to 55% saving of irrigation water for a significant increase in the yield of potato tubers. The water saved can be used for irrigating additional area under cultivation. In addition, reduced weed growth by visual observation under drip irrigation and drip + mulch system saves 40 to 50%, respectively in the labour cost engaged for weeding operations. Drip irrigation system costs rupees 25,000/- and life of the system is 10 years. Mulch costs rupees 2500/- each year. Potato produce grown under drip costs rupees 600/- per sack containing 100 kg potato (mixed grade) compared to potato under furrow irrigation (Rupees 400/-). On the basis of cost benefit analysis, use of mulch was discarded and drip irrigation system was found suitable for potato production.

4. Conclusion

Potato crop differed both in the maximum leaf area achieved and the duration of the canopy maintained in different irrigation treatments. Water deficit in alternate furrow irrigation reduced the rate of canopy expansion and maximum leaf area achieved, above-ground biomass, tuber growth and consequently the total tuber yield as well as tuber grade in comparison to well watered controls. Further, it is concluded that drip irrigation system is a viable tool for leaf area modification and source-sink alteration, stimulating early stolon initiation combined with an ability to quick ground cover and sustain leaf growth for new tuber initiation for seed production as well as extended tuber bulking of early formed tubers for obtaining maximum yield with 50% saving of irrigation water (133.76 mm, 282.40 mm and 325.80 mm as depth of water through drip, alternate furrow and furrow irrigation; respectively). Optimum leaf area and its duration influenced the extent of photosynthesis, evaporation, transpiration, stolon and tuber initiation, final biomass, and partitioning of dry matter into economic yield.

Acknowledgement

The author is thankful to Indian Council of Agricultural Research for financial support by providing ICAR Cess Fund for this study in Water Technology Centre at IARI, New Delhi.

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Table 1. Influence of drip irrigation and mulch combined with furrow, alternate furrow, and drip irrigation system on cumulative water use (cm), total tuber yield (t/ha) and water use efficiency (kg/ha/cm) of potato at maturity

Treatments	Cumulative water use	Tuber yield	Water use efficiency
	(cm)	(t/ha)	(kg/ha/cm)
Furrow	36.79	12.78	34.73
Furrow +mulch	35.7	12.83	35.92
Alternate furrow	37.87	10.35	27.33
Alternate furrow + mulch	35.67	11.10	31.12
Drip	21.90	24.95	113.93
Drip + mulch	16.83	26.02	154.60
CD at 5%	10.87	1.949	9.41
LSD (P=<0.001)	<	<	<
F test	**	**	**

** Significant at 0.01%

Ton (t) = 1000 kg

Table 2. Influence	of drip	irrigation	and mulc	h combined	with	furrow,	alternate	furrow,	and	drip	irrigation
system on leaf area	(cm^2) of	f potato at o	different d	ays after sov	ving						

Treatments	Days after sowing					
	25	40	60	80		
Furrow	814	2827	3841	4208		
Furrow + mulch	2039	6026	8149	4395		
Alternate furrow	828	2873	3018	3470		
Alternate furrow + mulch	1229	4173	6119	4028		
Drip	1628	4529	4275	3694		
Drip + mulch	2524	7593	8731	4869		
CD at 5%	180.9	659.5	748.4	587.4		
LDS (P=<0.001)	<	<	<	<		
F test	**	**	**	**		

** Significant at 0.01%



Figure 1. Number of tubers of different size per potato plant at final harvest under furrow, alternate furrow, drip irrigation, and mulch combined with each irrigation system (Error bars indicate SE)

Note:

L - Large tuber weight:(F=60 g; FM=50 g; AF=50 g; AFM=54 g; D=77 g; DM=75 g)M - Medium tuber weight:(F=8 g; FM=12 g; AF=11 g; AFM=9 g; D=17 g; DM=16 g)S - Small tuber weight:(F=3 g; FM=4 g; AF=5 g; AFM=3 g; D=4 g; DM=3 g)



Figure 2. Total number of stolons per potato plant under furrow, alternate furrow, drip irrigation, and mulch combined with each irrigation system; at different days after sowing (Error bars indicate SE)



Figure 3. Total dry weight of stolons (g) per potato plant under furrow, alternate furrow, drip irrigation, and mulch combined with each irrigation system; at different days after sowing (Error bars indicate SE)