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RESEARCH ARTICLE

Root aeration improves yield and water use efficiency of irrigated potato in sandy clay loam soil

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Abstract

A field study was conducted in 2012 and 2013 to evaluate the effect of air-injection into the irrigation stream in subsurface trickle irrigation on the productivity of potato. The growth characteristics, yield and water use efficiency (WUE) of potatoes grown in a sandy clay loam soil with subsurface trickle irrigation with an air-injection treatment were compared with those of potatoes grown under a conventional trickle and subsurface trickle irrigation as a control. The yield was 27.11% and 17.8% greater, in the air injection treatment comparing with non-aerated treatments trickle irrigation (DI) and subsurface trickle irrigation (SDI) respectively, for the first season, while it was greater by 38.2% and 7.66% than DI and SDI, respectively, for the second season. The WUE was 46.41% and 30.52% greater, in the air injection treatment comparing with non-aerated treatments (DI) and (SDI) respectively, for the first season, while it was greater by 61.78% and 19.33% than DI and SDI, respectively, for the second season. The plant height was 14.7% and 6.07% greater, in the air injection treatment than in the control (DI) and (SDI) respectively, for the first season, while it was greater by 14.13% and 9.7% than in the control for the second season. The shoot fresh weight per plant was 14.8% and 4.61% greater, aerated treatment than in DI and SDI respectively, for the first season, while it was greater by 37.6% and 1.94% for the second season. Data from this study indicate that potato yield can be improved under SDI if the drip water is aerated.

Introduction

Potato rates fourth among the world's agricultural products in production volume **(Faberio *et al.*, 2001)**. According to World Potato Center's research, worldwide demand for potatoes will exceed that of rice, wheat, or corn by 2020. The total food value of potato per acre is high. The total caloric contribution of potato to the world food supply will remain less than these cereal crops due to higher water content of the potato.

Currently, world food production depends heavily on irrigated agriculture. Only 20% of the world's farmland is irrigated, but that farmland produces 40% of the world's food supply **(Howell, 2001)**. The highest yields obtained from irrigation are more than double the highest yields for rainfed agriculture.

In spite of this, it is very unlikely that irrigated agriculture as it is currently practiced can provide food for the projected increased food demand with population growth to 9 billion by 2050 it will need to encompass increased irrigation efficiency and enhanced use efficiency of other production inputs **(Horrigan *et al.*, 2002)**.

In spite of the great scope for SDI, and adoption of in itself , it is not an ideal irrigation system. By the very fact that water is continuously emitted, for durations that vary depending upon soil type, crop, and evaporative demand, a part of the root zone in SDI, particularly in heavy clay soils, is purged of soil water and therefore experiences insufficient oxygen for root and microbial respiration and root growth. Quite evidently the point source application of irrigation water with SDI will impose a great impact on the soil moisture gradient and on root activity as affected by the overall soil oxygen distribution pattern. Indeed, **Silberbush *et al.* (1979)** showed how the root system of trickle irrigated crops was concentrated on the periphery of the irrigated soil volume, in line with data that showed a low oxygen diffusion rate in the central portion of the irrigated soil volume. Nevertheless, **Bar-Yosef *et al.* (1989)** and **Hutmacher *et al*. (1998)** found that roots still to be concentrated around emitters in corn and cotton crops. Once air returns to that zone it will be the zone most favorably supplied by water. **Machado *et al.* (2003)** indicated that roots preferentially colonize the soil volume at the depth of the emitters in SDI crops, not only because that soil volume has preferential supply of water, but also because the fertilizer requirements of the crops are frequently supplied together in trickle irrigation water.

Oxygation is the process of aerating irrigation water and employing SDI to deliver it to the root zone. Hyper-aerating irrigation water to increase the oxygen concentration is accomplished by either mixing air or by mixing peroxides such as hydrogen peroxide (H_2O_2) with irrigation water before it is distributed through the irrigation lines. Oxygation offers plant roots and soil biota extra oxygen with water during, or prior to, finishing each irrigation cycle, when soil air has been replaced by irrigation water. With the current oxygation technology, the additional oxygen is provided directly into the rhizosphere during irrigation with air injection into the irrigation stream **(Goorahoo *et al.*, 2002)**, or close to the end of each irrigation cycle as with hydrogen peroxide injection **(Huber, 2000)**.

Soil aeration and the effect of soil hypoxic conditions on plants have been studied for decades **(Grable, 1966; Armstrong, 1979; Glinski and Stepniewski, 1985; Bhattarai *et al.*, 2005b)**. Also, several means of improving soil aeration have been developed, including: improving soil structure through tillage **(Abu-Amdeh, 2003)**, creating artificial aeration pathways **(Ben-Gal *et al*., 2004; MacDonald *et al*., 2004)**, irrigation and drainage management **(Camp, 1998; Ayars *et al*., 1999)** and plant selection for tolerance **(Stepanova *et al*., 2002)**. In particular, three major methods for enriching the root zone with O_2 by subsurface trickle irrigation (oxygenated SDI) have been proposed: forced aeration, i.e., pumping pressurized air into the trickle lines **(Melsted *et al*., 1949; Busscher, 1982)**, sucking air (bubbles) into the irrigation water entering the trickle lines **(Goorahoo *et al*., 2002; Bhattarai *et al*., 2004, 2006; Maestre-Valero and Martinez-Alvarez, 2010; Bonachela *et al*., 2010)**, and adding various peroxides (e.g., H_2O_2, urea peroxide, potassium peroxide) to the irrigation water **(Melsted *et al*., 1949; Herr and Jarrel, 1980; Bryce *et al*., 1982; Bhattarai *et al*., 2004; Urrestarazu and Mazuela, 2005)**. Most of these studies reported impressive yield increases for several crops and soil types, but none of the proposed methods has been established in agricultural practice, and it is likely that hypoxic root zones still reduce yields in some circumstances.

The amount of air present in the soil is directly influenced by soil texture. Aggregate size and degree of compaction directly influence the volumetric air content of soil **(Fernhout and Kurtz, 1999)**, and compacted soils in general have reduced pore space. Smaller soil particles (such as silt and clay) reduce soil aeration because they pack together very tightly, directly limiting the air spaces between them and indirectly as they hold more water against drainage forces **(Rengasamy, 2000)**. Larger soil particles (sand), aggregates, and organic matter increase soil aeration because they leave gaps in the soil volume that can be easily drained and filled by air **(Cogger *et al*., 1992).** In sandy soils at field capacity, soil air comprises 25% or more on a soil volumetric basis. However, if there is too much natural soil aeration, evaporation and leaching would rise and the soil would soon dry out **(Brady and Weil, 1999; Fernhout and Kurtz, 1999)**. In loamy soils, the volumetric air content is between 15 and 20%, and in clayey soils that tend to retain the most water, it can fall below 10% of the total soil volume at field capacity**(Peverill, 1999)**.

In the main, benefits to oxygation accrue on heavy soil, but where trialled on lighter textured fine sandy loam soils, benefits have been notable **(Goorahoo *et al.*, 2002)**. Tape depths for SDI range from 0.2 to 0.7 m **(Camp, 1998)**, with the depth optimized for local conditions, and generally deeper for multiple year use. In a production system where the trickle tape was placed 5 cm below the soil surface, forced air did not result in growth or yield benefit **(Heuberger *et al*., 2001)**, but benefits to oxygation are unlikely to be influenced by deeper tape depth, for the additional oxygen is made available close to the emitter and root mass. Experiments by **Goorahoo *et al*. (2002) and (Heuberger *et al*. (2001)** showed oxygation benefits with trickle tape at 12–15 cm depth, and studies by **Bhattarai**

***et al*. (2004)** illustrated oxygation benefits at tape depth from 8 cm to 25–30 cm. Field data with bell pepper showed that the increase in production due to aeration reached a maximum value at 25 m from the aeration source. Yield then declined along the next 35 m, equaling at the end of the row the yield of non-aerated plots. Such a decline may be acceptable under the shorter row lengths in the glasshouse industry, but emitter design may need to be modified to induce greater uniformity for extensive agriculture **(Goorahoo *et al*., 2002)**. Leaf chlorophyll concentration increases with oxygation, and specific leaf area (SLA) tends to decrease **(Bhattarai *et al*., 2004)**. Greater leaf chlorophyll concentration and SLA have been correlated with the potential to accumulate high plant biomass **(Terauchi *et al*., 2001)**.

In oxygation (venturi and hydrogen peroxide) trials with tomato, soybean and cotton on a heavy clay soil, average yield increases of 12, 84, and 21%, respectively, were achieved compared to the control **(Bhattarai *et al*., 2004)**. Similarly, in a field experiment at the Centre for Irrigation Technology, in a loam and sandy loam soil, oxygation (venturi) led to a 33% increase in bell pepper count and a 39% increase in total fruit weight **(Goorahoo *et al*., 2002)**. Likewise, in a field experiment on a soil with air-filled porosity at field capacity of 6% with cauliflower conducted in Germany using trickle tape at 15 cm depth, total dry matter and percentage of large curds tended to be higher with forced injection of atmospheric air (45 min at 50 kPa after each irrigation and after rainfall if exceeding 10 mm) compared with no aeration. In the same experiment, sweet corn produced a higher proportion of marketable cobs with aeration, and of the cobs unsuitable for fresh market, a higher proportion was suitable for industrial processing.
Although recognized for its greater WUE than other forms of irrigation, the WUE of SDI is further improved by oxygation. Hypoxia that restricts root growth reduces the ability of the root system to capture water, thereby predisposing greater volumes to drainage, leakage, and contamination of ground water, with concomitant loss of WUE. Oxygation promotes root growth in the rooting zone of SDI crops, and can reduce some of the undesirable deep drainage. Season-long water use efficiency was considerably higher with oxygation by 11% (39.1 versus 35.2 g L^{-1}) for tomato, by 70% (3.65 versus 2.15 g L^{-1}) for vegetable soybean, and by 18% (0.45 versus 0.38 g L^{-1}) for cotton on a heavy clay soil **(Bhattarai et al., 2004; 2005a)** and by 36% (1.463 versus 0.937 kg m^{-3}) for corn on a sandy clay loam soil **(Abuarab *et al.*, 2012)**. The other measures of WUE (e.g., the quotient of leaf net photosynthesis and transpiration) were also higher with oxygation **(Bhattarai *et al*., 2004)**. Although data on the instantaneous WUE showed that oxygated crops were more conservative in their water use per unit of CO_2 fixed in photosynthesis, and because of greater canopy transpiration, they were greater users of water, with all the benefits that brought to the hypoxic soil environment.

The major goal of this study was to evaluate the technical feasibility of injection of ambient air into a subsurface trickle irrigation tape, as a best management practice for improving growth characteristics, crop production and water use efficiency of potato.

MATERIALS AND METHODS

1. Location and soil of experimental field plot

A field study was conducted from October to February 2011-2012 and 2012-2013 at Research Unit of Agricultural Engineering Department (latitude 30.0861N, and longitude 31.2122E, and mean altitude 70 m above sea level), Faculty of Agricultural, Cairo University, Egypt. Soil samples from surface down to 60 cm at 20 cm interval were collected. Hydrometer method was followed to determine the sand, silt and clay percentage of soil. The soil of the experimental area was deep, well-drained sandy clay loam (Table 1). Irrigation water was obtained from a deep well (60 m depth from the soil surface) located in the experimental area, with pH 7.2, and an average electrical conductivity of 0.83 dS m^{-1}. Weather data of the experimental site for 2 growing seasons are presented in Table 2.

Table 1. Some physical and chemical properties of the experimental soil

Soil depth (cm)	Texture	Field capacity (cm^3 cm^{-3})	Wilting point (cm^3 cm^{-3})	Bulk density (g cm^{-3})	pH	EC_e (dS m^{-1})
0 – 20	SCL	42.07	14.43	1.29	7.74	2.43
20 – 40	SCL	41.80	14.91	1.31	7.69	1.92
40 - 60	SCL	38.96	17.15	1.33	7.81	1.78

Table 2. Monthly climatic data for the growing seasons of the experimental area

Year	Climate parameter	Month					
		Oct.	Nov.	Dec.	Jan.	Feb.	Mar.
2011-2012	T_{min}. (^{0}C)	18.55	15.84	13.97	12.64	12.25	12.21
	T_{max} (^{0}C)	29.56	26.50	24.53	23.11	22.63	22.71
	T_{ave} (^{0}C)	23.83	20.94	18.99	17.52	17.07	17.08
	RH (%)	55.29	59.80	62.75	61.90	61.12	60.00
	Sun shine (h)	11.2	10.6	10.1	10.3	11.2	11.7
2012-2013	$T_{min.}$ (^{0}C)	22.2	17.8	9.1	7.3	7.2	8.2
	T_{max} (^{0}C)	34.4	29.4	22.6	24.1	26.4	30.3
	T_{ave} (^{0}C)	28.4	23.4	19.7	15.3	16.4	17.6
	RH (%)	60	69	63.4	66	56	56
	Sun shine (h)	11.4	10.7	10.4	10.5	11.3	11.9

Table 3. Hydraulic characteristic of the trickle irrigation system

Irrigation system	**Characteristics**	**Description**
Trickle Tape	Wall thickness (mm)	0.3
	Tape inner diameter (mm)	16
	Minimum operating pressure (kPa)	30
	Maximum operating pressure (kPa)	105
	Dripper discharge (Lph)	0.75
	Spacing between two drippers (cm)	30.0
	Spacing between two tapes (cm)	75.0
	Depth of placement of trickle tape (cm)	20.0

2. System installation and experimental treatments

A field plot of size 67.5m × 30m was selected for experimental studies. The field plot was divided into nine equal plots of 7.5 m × 30 m. Each plot included 10 rows, 0.75 cm apart, representing a single treatment. The experiment was laid in the split plot design with 3 treatments (surface trickle irrigation (I_1), subsurface trickle irrigation (I_2) and Air injection under subsurface trickle irrigation (I_3)) and 3 replications (R_1, R_2 and R_3) of each treatment. Installation of the SDI system commenced in October 2011 with control facility, which included hydro cyclone filter, screen filter, back flush mechanisms, fertilizer injection system, i.e. venture. Care was taken to place the trickle tape straight in the ridges with openings on the upper side of the trickle tapes.

Tubers of 30 g weight of potato (var. Diamont) were planted at the depth of 10 cm in the raised ridges prepared during the third week of October at a tuber and ridge spacing of 20 cm × 75 cm. The base width and height of ridges were kept 60.0 and 30.0 cm, respectively.

Trickle tape of 0.3 mm thickness (T-Tape, Australia, model TSX 515-30-250) was buried manually at depths of 20 cm in the middle of ridges formed for sowing of potato under different treatments. The hydraulic characteristics of installed trickle system are given in Table 3. The installed trickle system had drippers spaced at 30 cm each with an application rate of 250 Lph/100m. Time domain reflectometry (TDR) was used in this study for determination of soil water content. Three access tubes, one at the middle of ridge and two at 15.0 and 30.0 cm away from the middle of ridge were installed. Access tubes were placed at the middle of the row up to a depth of 0.60 m and water content (volumetric) was measured in all treatments. The root zone soil moisture was calculated for each soil based on the difference between field capacity and measured soil moisture content. For the whole growing season irrigation depth was determined to replenish 100% of plant available water in the root zone.

3. Nutrient management

Fertilizers were consisting of 180 kg N ha^{-1}, 100 kg P_2O_5 ha^{-1} and 150 kg K_2O ha^{-1}. The potassium was applied in two splits (half at planting and half at earthing up) because this practice gives better results than if the entire doses were applied at planting **(Phillips et al., 2004)**. Following the recommended practice of fertilizer application, nitrogen was applied into two split doses (one-third at planting and two-third at crop emergence stage).

4. Estimation of uniformity of trickle system

Tests for uniformity of water application the trickle system were carried out, in the month of October every year. For each testing, 30 drippers were selected from head, middle and tail ends of trickle tape, randomly. Uniformity of water application was determined from the dripper outflow collected in cans for a known duration. The uniformity of water application was calculated from the statistical distribution of dripper flow rates in terms of coefficient of variation (CV) and distribution uniformity (DU) using Eqs. (1) and (2), as follows:

$$CV = \frac{S}{q} \qquad (1)$$

$$DU = (\frac{q_{lq}}{q}) \times 100 \qquad (2)$$

Where s is the standard deviation of drippers discharge (Lph); q the mean dripper flow rate (Lph) and q_{lq} is the mean of lowest one-fourth of drippers discharge (Lph). Five microirrigation uniformity classifications, ranging from excellent to unacceptable, recognized by the American Society of Agricultural Engineers **(ASAE, 1996 a, b)** were used to evaluate the DI and SDI systems.

5. Air *injection*

An air compressor and an air volume meter were used as air-injector unit. They were installed in-line immediately after a gate valve. The air volume meter consists of a 1 m length pipe with a diameter of 2 inches, and is used to transform the flow from turbulent to laminar. An air velocity sensor is installed in the centre of the pipe and is used to measure the average velocity (Fig. 1). This way can control the amount of air injected into the irrigation line (12% air by volume of water). Aerated water was delivered to the soil through drippers. The water flow was decreased when air was injected and then the time of irrigation was increased to compensate the decrement of water flow.

6. Data recording

At the day of final harvest on 28 February (110 days after planting (DAP)), 18 plants were harvested from each plot by taking six plants from each of the beginning, middle and end of the plot respectively, for yield mass determination. Total fresh weight of the tubers was determined (kg per plant) and the tuber was dried at 85 ^{o}C for 24 h to determine the carbohydrates and sugars, soluble and non-soluble. One plant per plot was harvested for determination of shoot fresh weight (g) and shoot dry weight (g). The chlorophyll was measured by using “Minolta Chlorophyll Meter”, SPAD-502 (Spectrum Technologies). The data for plant height, number of aerial stems, fresh weight per plant and dry weight per plant was derived from final plant harvest. Actual evapotranspiration within the growing period was estimated from the soil water balance from the following equation:

$$ET = I + P \pm \Delta SW - Dp - R \qquad (3)$$

Where ET is the evapotranspiration (mm), I the amount of irrigation water applied (mm), ΔSW the soil water content changes (mm), Dp the deep percolation (mm), and R is the amount of runoff (mm). Since the amount of irrigation water was controlled, deep percolation and runoff were assumed to be negligible. Water-use efficiency (WUE) and irrigation water-use efficiency (IWUE) values were calculated with Eqs. (4) and (5), respectively **(Howell *et al*., 1990)**.

$$\text{WUE} = (\frac{E_y}{E_t}) \times 100 \qquad (4)$$

Where WUE is the water use efficiency (t ha^{-1} mm^{-1}); E_y is the economical yield (t ha^{-1}); E_t is the plant water consumption, mm.

$$IWUE = (\frac{E_y}{I_r}) \times 100 \quad (5)$$

Where IWUE is the irrigation water use efficiency (t ha^{-1} mm^{-1}), E_y is the economical yield (t ha^{-1}), I_r is the amount of applied irrigation water (mm).

7. Statistical Analyses

Statistical analyses were carried out using the GLM (General Linear Model) procedure of the SPSS statistical package. The model was used for analyzing growth characteristics, yield, WUE, and IWUE as fixed effects for the irrigation treatments and growing seasons and the interactions between them, and the replications as error term **(Snedecor and Cochran 1976)**. The probability level for determination of significance was 0.05.

RESULTS AND DISCUSSIONS

1. Irrigation and yield

The characteristics of water use and yield showed a significant differences between seasons (S_1) and (S_2) except for water use (ET) and irrigation water use efficiency (IWUE), on the other hand, there were significant differences between irrigation treatments for air injection treatment (I_3) and both DI (I_1) and SDI (I_2), while for the interaction between seasons and irrigation treatments there were significant differences between the aerated and non-aerated treatments (Table 4).

Table 4. Total irrigation water amount (I), plant water consumption (ET), yield, irrigation water use efficiency (IWUE) and water use efficiency (WUE) of potato for different growing seasons and irrigation treatments.

Treatments	I (m^3 ha^{-1})	ET (m^3 ha^{-1})	Yield (ton ha^{-1})	IWUE (kg m^{-3})	WUE (kg m^{-3})
S_1	6259.760 b	5987.440	33.677 a	5.451	5.666 a
S_2	6277.010 a	5968.047	32.487 b	5.243	5.510 b
LSD	15.50	NS	0.693	NS	0.1095
I_1	6713.955 a	6377.260 a	28.372 c	4.242 c	4.450 c
I_2	6372.510 b	6062.440 b	33.335 b	5.235 b	5.478 b
I_3	5718.690 c	5493.530 c	37.538 a	6.565 a	6.835 a
LSD	9.429	10.87	1.103	0.07292	0.2019
S_1I_1	6697.210 b	6358.120 b	30.157 e	4.533 e	4.740 d
S_1I_2	6372.400 c	6077.090 c	32.540 d	5.110 d	5.317 c
S_1I_3	5709.670 e	5527.110 e	38.333 a	6.710 a	6.940 a
S_2I_1	6730.700 a	6396.400 a	26.587 f	3.950 f	4.160 e
S_2I_2	6372.620 c	6047.790 d	34.130 c	5.360 c	5.640 b
S_2I_3	5727.710 d	5459.950 f	36.743 b	6.420 b	6.730 a
LSD	13.34	15.37	1.559	0.1031	0.2855

Note: Numbers followed by different letters with in the growing seasons and irrigation treatments are statistically different ($P < 0.05$).

There was a 14.75% and 10.4% decrease in irrigation water (I) of potatoes, in the air injection treatment (S_1I_3) comparing with non-aerated treatments trickle irrigation (S_1I_1) and subsurface trickle irrigation (S_1I_2), respectively, for the first season, while it was lower by 14.9% and 10.12% than S_2I_1 and S_2I_2, respectively, for the second season. The water use (ET) was 13.1% and 9.05% lower, in (S_1I_3) treatment than in S_1I_1 and S_1I_2 treatments, respectively, for the first season, while it was lower by 14.64% and 9.72% than S_2I_1 and S_2I_2 treatments respectively, for the second season (Table 4).

The yield was 27.11% and 17.8% greater, in the air injection treatment (S_1I_3) comparing with non-aerated treatments trickle irrigation (S_1I_1) and subsurface trickle irrigation (S_1I_2), respectively, for the first season, while it was greater by 38.2% and 7.66% than S_2I_1 and S_2I_2, respectively, for the second season. The percentage increases observed in this study can potentially translate into a projected increase benefits per hectare for the farmer depending on the wholesale price of potato (Table 4).

The IWUE was 48.03% and 31.31% greater, in the air injection treatment (S_1I_3) comparing with non-aerated treatments (S_1I_1) and (S_1I_2), respectively, for the first season, while it was greater by 62.53% and 19.78% than S_2I_1 and S_2I_2, respectively, for the second season. On the other hand, the WUE was 46.41% and 30.52% greater, in the air injection treatment (S_1I_3) comparing with non-aerated treatments (S_1I_1) and (S_1I_2), respectively, for the first season, while it was greater by 61.78% and 19.33% than S_2I_1 and S_2I_2, respectively, for the second season (Table 4).
The yield improvement under aerated treatment comparing with non-aerated treatments is related to that oxygen (O_2) is essential for root respiration. Immediately after the roots have been surrounded by water they can no longer respire normally. The liquid impedes diffusion of metabolites such as carbon dioxide and ethylene. This causes the plant to be stunted because ethylene is a growth inhibitor **(Arkin, 1981)**. When air is injected into the water within the root zone, diffusion of ethylene and carbon dioxide away from the roots may be increased. This increased diffusion rate should result in improved growing conditions and so yield.

The WUE of SDI is further improved by air injection. Hypoxia that restricts root growth reduces the ability of the root system to capture water, thereby predisposing greater volumes to drainage, leakage, and contamination of ground water, with concomitant loss of WUE. Air injection promotes root growth in the rooting zone of SDI crops, and can reduce some of the undesirable deep drainage **(Bhattarai *et al*., 2005b)**.

2. Vegetative growth parameters
The characteristics of vegetative growth showed a significant difference between seasons except for number of aerial stems per plant and weight of tubers per plant. On the other hand, there were a significant differences between irrigation treatments for air injection treatment (I_3) and both DI (I_1) and SDI (I_2), while for the interaction between seasons and irrigation treatments most of vegetative parameters were not significant except shoot fresh weight per plant and weight of tubers per plant. In this respect, the highest values in all measured vegetative growth traits were recorded in case of using injection treatments compared with the other irrigation systems (Table 5).

The plant height was 14.7% and 6.07% greater, in the air injection treatment (S_1I_3) than in the trickle irrigation (S_1I_1) and subsurface trickle irrigation (S_1I_2), respectively, for the first season, while it was greater by 14.13% and 9.7% than S_2I_1 and S_2I_2, respectively, for the second season. The number of areal stems per plant was 22.52% and 16% greater, in (S_1I_3) treatment than in S_1I_1 and S_1I_2 treatments, respectively, for the first season, while it was greater by 26.47% and 19.46% than S_2I_1 and S_2I_2 treatments, respectively, for the second season. The plant height and number of areal stems were slightly higher in the air injection treatment, although the difference between air injection treatment and both trickle and subsurface trickle irrigation under growing seasons was not significant (Table 5).

The shoot fresh weight per plant was 14.8% and 4.61% greater, in S_1I_3 treatment than in S_1I_1 and S_1I_2 treatments, respectively, for the first season, while it was greater by 37.6% and 1.94% than S_2I_1 and S_2I_2 treatments, respectively, for the second season. However, the shoot dry weight per plant showed no significant difference between the air injection treatment and both trickle and subsurface trickle irrigation (Table 5).

The weight of tubers per plant was 27.7% and 18.5% greater, in S_1I_3 treatment than in S_1I_1 and S_1I_2 treatments, respectively, for the first season, while it was greater by 37.49% and 7.17% than S_2I_1 and S_2I_2 treatments, respectively, for the second season (Table 5).

Table 5. The vegetative growth parameters of potato in different growing seasons and irrigation treatments.

Treatments	Plant height (cm)	Number of aerial stems per plant	Shoot fresh weight per plant (g)	Shoot dry weight per plant (g)	Number of tubers per plant	Weight of tubers per plant (g)
S_1	63.422 b	2.589	379.522 a	47.478 a	5.511 a	739.444
S_2	65.578 a	2.511	355.678 b	44.174 b	5.011 b	716.367
LSD	2.105	NS	17.11	2.378	0.2585	NS
I_1	60.383 b	2.317 b	318.617 c	40.295 b	4.950 b	624.500 c
I_2	64.033 b	2.450 b	385.783 b	48.495 a	5.300 ab	732.933 b
I_3	69.083 a	2.883 a	398.400 a	48.495 a	5.533 a	826.283 a
LSD	4.306	0.242	9.841	4.369	0.3597	12.17
S_1I_1	58.933	2.367	350.833 c	44.297	5.167	661.467 e
S_1I_2	63.733	2.500	385.000 b	48.310	5.600	712.100 d
S_1I_3	67.600	2.900	402.733 a	49.827	5.767	844.767 a
S_2I_1	61.833	2.267	286.400 d	36.293	4.733	587.533 f
S_2I_2	64.333	2.400	386.567 b	48.680	5.000	753.767 c
S_2I_3	70.567	2.867	394.067 ab	47.550	5.300	807.800 b
LSD	NS	NS	13.92	NS	NS	17.21

Note: Numbers followed by different letters with in the growing seasons and irrigation treatments are statistically different ($P < 0.05$).

The improvement of vegetative growth parameters under aerated treatment comparing with water only treatments is related to that poor root respiration reduces the uptake of water and nutrients, and because chemical changes in the soil produce toxins that limit overall plant growth **(Fernhout and Kurtz, 1999)**, poor soil aeration induces a wider effect on plant growth than that confined to root growth. At any given temperature, plant growth rate can be related to the oxygen level in the soil **(McLaren and Cameron, 1996)**. Most species show a decreased growth rate with a reduction in availability of soil oxygen. A primary manifestation of hypoxia is a reduction in stomatal conductance and water absorption **(Vasellati *et al*., 2001)**. This leads to reduced canopy transpiration. Indeed, rates of stem sap flow have been shown to increase with oxygation, an effect that probably has a positive feedback, diminishing the soil water content and thereby increasing oxygen flux from the atmosphere to roots.

3. Quality parameters

The characteristics of quality parameters i.e., specific gravity, chlorophyll, total carbohydrates, soluble and non-soluble sugars showed a significant difference between seasons. On the other hand, there was a significant differences between irrigation treatments for air injection treatment (I_3) and both trickle irrigation (I_1) and subsurface trickle irrigation (I_2), while for the interaction between seasons and irrigation treatments most of quality parameters were significant except chlorophyll (Table 6).

With respect to quality parameters, the specific gravity was 5.1% and 1,49% greater, in the air injection treatment (S_1I_3) than in the trickle irrigation (S_1I_1) and subsurface trickle irrigation (S_1I_2) treatments, respectively, for the first season, while it was greater by 8.06% and 5.49% than S_2I_1 and S_2I_2, respectively, for the second season. However, the chlorophyll showed no significant difference between the aerated and non-aerated treatments (Table 6).

The total carbohydrates were 40.52% and 21.24% greater; in the aerated treatment S_1I_3 than non-aerated treatments S_1I_1 and S_1I_2, respectively, for the first season, while it was greater by 39.10% and 21.09% than S_2I_1 and S_2I_2, respectively, for the second season (Table 6).

The soluble sugars were 21.63% and 16.12% greater, in the aerated treatment S_1I_3 than non-aerated treatments S_1I_1 and S_1I_2, respectively, for the first season, while it was greater by 25.72% and 2.8% than S_2I_1 and S_2I_2, respectively, for the second season. While for Insoluble Sugar there was 42.85% and 21.82% greater increase, in the aerated treatment S_1I_3 than non-aerated treatments S_1I_1 and S_1I_2, respectively, for the first season, while it was greater by 40.12% and 23.04% than S_2I_1 and S_2I_2, respectively, for the second season (Table 6).

Table 6. Specific gravity, chlorophyll, total carbohydrates, soluble sugar and insoluble sugar of potato in different growing seasons and irrigation treatments.

Treatments	**Specific gravity**	**Chlorophyll** (Spad)	**Total Carbohydrates (g 100g^{-1} DW)**	**Soluble Sugar (g 100g^{-1} DW)**	**Insoluble Sugar (g 100g^{-1} DW)**
S_1	1.070 b	54.067 b	52.28 b	5.367 b	46.91 b
S_2	1.104 a	56.867 a	59.23 a	6.767 a	52.36 a
LSD	0.0109	2.591	1.891	0.194	0.2190
I_1	1.053 c	54.167 b	47.10 c	5.383 c	41.72 c
I_2	1.085 b	55.617 ab	54.33 b	6.150 b	48.18 b
I_3	1.123 a	56.617 a	65.83 a	6.667 a	59.00 a
LSD	0.0094	1.477	0.4910	0.3036	0.4189
S_1I_1	1.040 d	52.200	44.00 f	4.933 c	39.07 f
S_1I_2	1.077 c	54.200	51.00 d	5.167 c	45.83 d
S_1I_3	1.093 b	55.800	61.83 b	6.000 b	55.83 b
S_2I_1	1.067 c	56.133	50.20 e	5.833 b	44.37 e
S_2I_2	1.093 b	57.033	57.67 c	7.133 a	50.53 c
S_2I_3	1.153 a	57.433	69.83 a	7.333 a	62.17 a
LSD	0.0133	NS	0.6944	0.4294	0.5924

Note: Numbers followed by different letters with in the growing seasons and irrigation treatments are statistically different ($P < 0.05$).

CONCLUSIONS

Air injection irrigation systems can increase root zone aeration and add value to grower investments in SDI. The increase in yields and potential improvement in soil quality associated with the root zone aeration implies that the adoption of the SDI-air injection technology primarily as a tool for increasing potato productivity.

These statistically significant results on a small plot (0.20 ha.) support reported results obtained on tests conducted on a commercial farm, and are sufficiently encouraging to justify follow-up fieldwork on larger plots. Further fieldwork should be performed on various plant types and should include air/water ratio, and soil root zone moisture, temperature, and nutrient status measurements.

Of special interest in the potential application of this air injection technology is the characterization of how the beneficial effect may vary with the length of trickle lines. Subsequent studies should attempt to monitor pressure and velocity changes along the trickle system and correlate these with plant yield and soil parameters.

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