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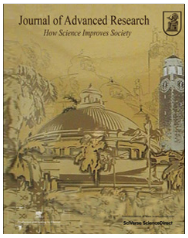

ORIGINAL ARTICLE

Effect of air injection under subsurface drip irrigation on yield and water use efficiency of corn in a sandy clay loam soil

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WUE

Abstract Subsurface drip irrigation (SDI) can substantially reduce the amount of irrigation water needed for corn production. However, corn yields need to be improved to offset the initial cost of drip installation. Air-injection is at least potentially applicable to the (SDI) system. However, the vertical stream of emitted air moving above the emitter outlet directly toward the surface creates a chimney effect, which should be avoided, and to ensure that there are adequate oxygen for root respiration. A field study was conducted in 2010 and 2011, to evaluate the effect of air-injection into the irrigation stream in SDI on the performance of corn. Experimental treatments were drip irrigation (DI), SDI, and SDI with air injection. The leaf area per plant with air injected was 1.477 and 1.0045 times greater in the aerated treatment than in DI and SDI, respectively. Grain filling was faster, and terminated earlier under air-injected drip system, than in DI. Root distribution, stem diameter, plant height and number of grains per plant were noticed to be higher under air injection than DI and SDI. Air injection had the highest water use efficiency (WUE) and irrigation water use efficiency (IWUE) in both growing seasons; with values of 1.442 and 1.096 in 2010 and 1.463 and 1.112 in 2011 for WUE and IWUE respectively. In comparison with DI and SDI, the air injection treatment achieved a significantly higher productivity through the two seasons. Yield increases due to air injection were 37.78% and 12.27% greater in 2010 and 38.46% and 12.5% in 2011 compared to the DI and SDI treatments, respectively. Data from this study indicate that corn yield can be improved under SDI if the drip water is aerated.

Introduction

Modifying root zone environment by injecting air has continued to intrigue investigators. However, the cost of a single purpose, air-only injection system, separate from the irrigation system, detracts from the commercial attractiveness of the idea. With the acceptance of subsurface drip irrigation (SDI) by commercial growers, the air injection system is at least

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potentially applicable to the SDI system. Unfortunately, when air alone is supplied to the SDI system it emits as a vertical "stream," moving above the emitter outlet directly to the soil surface. Consequently, the soil volume affected by air is probably limited to a chimney column directly above the emitter outlet. In this way, air and oxygen can continuously be supplied in solution and as micro bubbles, to root zone through the drip tape. Quite simply, subsurface drip irrigation (SDI) facilitates the delivery of aerated water directly to the root zone. This is defined as "oxygation." It can potentially overcome problems associated with low oxygen in the rhizosphere as induced by flooding, by irrigation itself, by salinity, sodicity, and by compaction [1–4].

The roots of most crop species need a good supply of oxygen in order to satisfy the water and nutrient needs of the shoots [5]. Paradoxically, one of the first symptoms of excessive soil wetness (i.e. saturation) is drought stress in the leaves. If these conditions are prolonged for more than a few days, then further serious damage can be affected via nutrient deficiency, build-up of metabolic poisons and increased incidence of root diseases [6]. Oxygen is essential for root respiration. Immediately after the roots have been surrounded by water they can no longer respire normally. The liquid also impedes diffusion of metabolites such as carbon dioxide and ethylene. This causes the plant to be stunted because ethylene is a growth inhibitor [7]. When air is entrained 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.

As drip irrigation develops a wetting front near emitters, the root zone of the crop remains near-saturation for a portion of the time between irrigation events, especially on heavy cracking clay (e.g. Vertisols) making them the least desirable soil types for drip irrigation. Particularly in poorly drained soils, flood irrigation and wet weather cause water to replace air in the soil thus reducing the availability and mobility of oxygen that remains trapped in soil pores [5]. By decreasing the supply of soil oxygen to plant roots, heavy rainfall or irrigation on such soils can constrain yields to well below their potential [8].

Subsurface drip irrigation (SDI) can significantly affect corn yields. For example increased with irrigation up to a point where irrigation became excessive; water use efficiency (WUE) increasing non-linearly with seasonal crop evapotranspiration (ETc) [9]. WUE was more sensitive to irrigation during the drier season and irrigation water use efficiency (IWUE) decreased sharply with irrigation. Irrigation significantly affected dry matter production and partitioning of the different corn plant components (grain, cob, and stover) [9].

Plant roots require adequate oxygen for root respiration as well as for sound metabolic function of the root and the whole plant. SDI minimizes alternate wetting and drying of the soil surface, a phenomenon that might otherwise predispose them to the cracking that could locally alleviate the lack of aeration. By direct injection of air in irrigation water, and by irrigation of a crop with aerated water, aeration of the crop root zone can now become a reality [1]. Injection of air alone is expensive and the injected air moves away from the root zone due to the chimney effect [3].

Oxygation is the delivery of aerated water by way of SDI systems [1,2]. Aerated through a venturi principle, or with solutions of hydrogen peroxide, SDI provided yield benefits to a range of crops including cotton, zucchini and vegetable soybean [1,2]. The reported studies on irrigation so far fail to offer an option for substantial reduction in water use while maintaining crop production. In a recent report on glasshouse and field experiments, [1,2] confirmed that dramatic increases in crop yields, water use efficiency and salinity tolerance could be achieved with the use of oxygenated subsurface drip irrigation water, especially for crops grown on heavy clay soils [1,2]. These researches showed that for soybean, oxygation increased water use efficiency (WUE) (yield divided by seasonal ET) by 54% and 70%, respectively, for hydrogen peroxide application and air injection using a venturi valve, and pod yield by 82% and 96%, respectively, for the two treatments. Likewise, for crops grown across a range of saline soil conditions, aeration using the venturi principle resulted in yields superior to those of the non-aerated controls [10]. Benefits of aeration using the venturi principle in California [3,11], or using hydrogen peroxide in Germany [12] on crop growth have also reported.

Aeration of subsurface drip irrigation water, using appropriate techniques such as the venturi, is a significant recent approach to economize on large-scale water usage and minimize drainage in irrigated agriculture [13].

Recent and ongoing research has shown that the incorporation of air injectors in SDI systems can increase root zone aeration and add value to grower investments in SDI. Accordingly the aim of this study was firstly to evaluate the technical feasibility of injection of ambient air into a subsurface drip irrigation tape, as a best management practice for improving growth characteristics and crop production of corn (*Zea mays L.*). Secondary to assess the effect of air injection on soil penetration resistance and plant take off force.

Material and methods

An open field experiment was carried out through installing an irrigation system that combined subsurface drip irrigation (SDI) tape and an air injection system that mixes air with the water delivered within the root zone.

Location, soil, and crop details

The experiment was carried out at Cairo University, Faculty of Agriculture, Agricultural Engineering Department experimental station at El-Giza governorate, Egypt (latitude 30.0861N, and longitude 31.2122E, and mean altitude 70 m above sea level). The corn variety Hybrid single 10 was directly sown on 22 April in both growing seasons 2010 and 2011. Plants were spaced 30 cm × 60 cm within and between rows, respectively.

The experimental area has an arid climate with cool winters and hot dry summers. Table 1 summarizes the monthly mean climatic data for both growing seasons 2010 and 2011 for the city of El-Giza.

No rainfall was recorded in either of the 2010 and 2011 growing seasons, and the irrigation water was applied in 2010 and 2011 during the April–July growing season.

The soil at the experimental site is classified as a sandy clay loam. Physical and chemical properties of the experimental soil are given in Table 2. 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}.

Table 1 Monthly growing season climatic data for the experimental area.

Month	Mean temperatures (°C)						Relative humidity (%)	Sun shine (h)
	Minimum		Maximum		Average			
	2010	2011	2010	2011	2010	2011		
April	16.0	10.9	29.6	31.7	23.1	21.3	50.0	12.8
May	19.2	14.3	33.9	34.4	26.5	24.4	47.0	13.5
June	22.7	18.9	37.0	36.5	30.0	27.7	52.0	13.9
July	23.2	21.8	38.2	39.3	30.7	30.6	56.0	14.3

Table 2 Physical and chemical soil properties of the experimental site.

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

Subsurface laterals were placed 20 cm under the soil surface in a trench prepared with an AFT45 tractor mounted trencher (AFT Trenchers Ltd., Sudbury, England), laterals were placed at 60 cm between each other. Then the trenches were carefully backfilled with the previously removed soil. The lateral was 16 mm external diameter and 60 m long, the space between emitters was 20 cm, the emitter type was Supertif (Netafim, Israel), that were replicated three times in the experiment for each treatment. The emitter features were: 3.85 $l\ h^{-1}$ flow rate, turbulent flow, completely flow regulated with outstanding clogging resistance, a working pressure of 100 kPa, and a built-in no-drain device which prevents water draining from the drip line when water has been shut off.

Daily soil water balance and ETc were estimated with a computer software CropWat program. The inputs to the program were daily weather data, including rainfall, irrigation date and amounts, initial water content in the soil profile at crop emergence, and crop and site-specific information such as planting date, maturity date, soil parameters, maximum rooting depth. The CropWat program calculated daily ETc. This procedure calculates ETc as the product of the evapotranspiration of a grass reference crop (ET_o) and a crop coefficient (K_c). ET_o was calculated using the weather data as input to the Penman–Monteith equation and the K_c was used to adjust the estimated ET_o for the reference crop to that of other crops at different growth stages and growing environments.

Air injection

An air compressor and an air volume meter were used as the air-injector unit. They were installed in-line immediately after a gate valve. The air volume meter consisted of a 1 m length pipe with a diameter of 2 in., and was used to transform the flow from turbulent to laminar. An air velocity sensor was installed in the center of the pipe and was used to measure the average velocity (Fig. 1). This way it was possible to control the amount of air ingress 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 we increased the time of irrigation to compensate for the decrement of water flow.

Soil moisture monitoring

Soil moisture content was measured daily using a profile probe calibrated by way of the gravimetric method. The time domain reflectometry (TDR) Profile Probe consists of a sealed polycarbonate rod (25 mm diameter), with electronic sensors (seen as pairs of stainless steel rings) arranged at fixed intervals along its length. Soil moisture was measured 5 cm away from the emitter by using the TDR sensor. Soil moisture was maintained between the refill point (28% by volume) and field capacity (41% by volume). Irrigation was carried out on a 1–3 day interval, between 7:00 h and 12:00 h, based on the readings from the TDR.

Experimental design and treatments

The experiment comprised of corn was grown at field capacity with and without aeration; three treatments were applied, drip irrigation (DI), subsurface drip irrigation (SDI) and subsurface with air injection. The area for each treatment was 6 m * 60 m.

The nutrient requirement of the crop in both experiments was supplied through fertigation using piston pump power by the water pressure system. Fertilizers consisted of 200 $kg\ ha^{-1}$ actual N, 50 $kg\ ha^{-1}$ P_2O_5 and 60 $kg\ ha^{-1}$ K_2O. Starter fertilizer (10-50-10) was applied with the transplant water (500 g in 200 L water and approximately 116 ml of solution per plant).

Evaluation parameters

The emitters were evaluated by way of the coefficient of manufacturing variation (CV), by measuring the discharge of a random sample of 20 emitters under different operating pressures (0.75, 1, and 2 kPa) using the following equations:

$$C_V = \frac{S}{\overline{X}} \tag{1}$$

$$S = \left[\frac{\sum_{i=1}^{n}(X_i - \overline{X})^2}{n-1}\right]^{0.5} \tag{2}$$

where X_i is the discharge of an emitter, $\overline{X}$ the mean discharge of emitters in the sample and S is the standard deviation of the

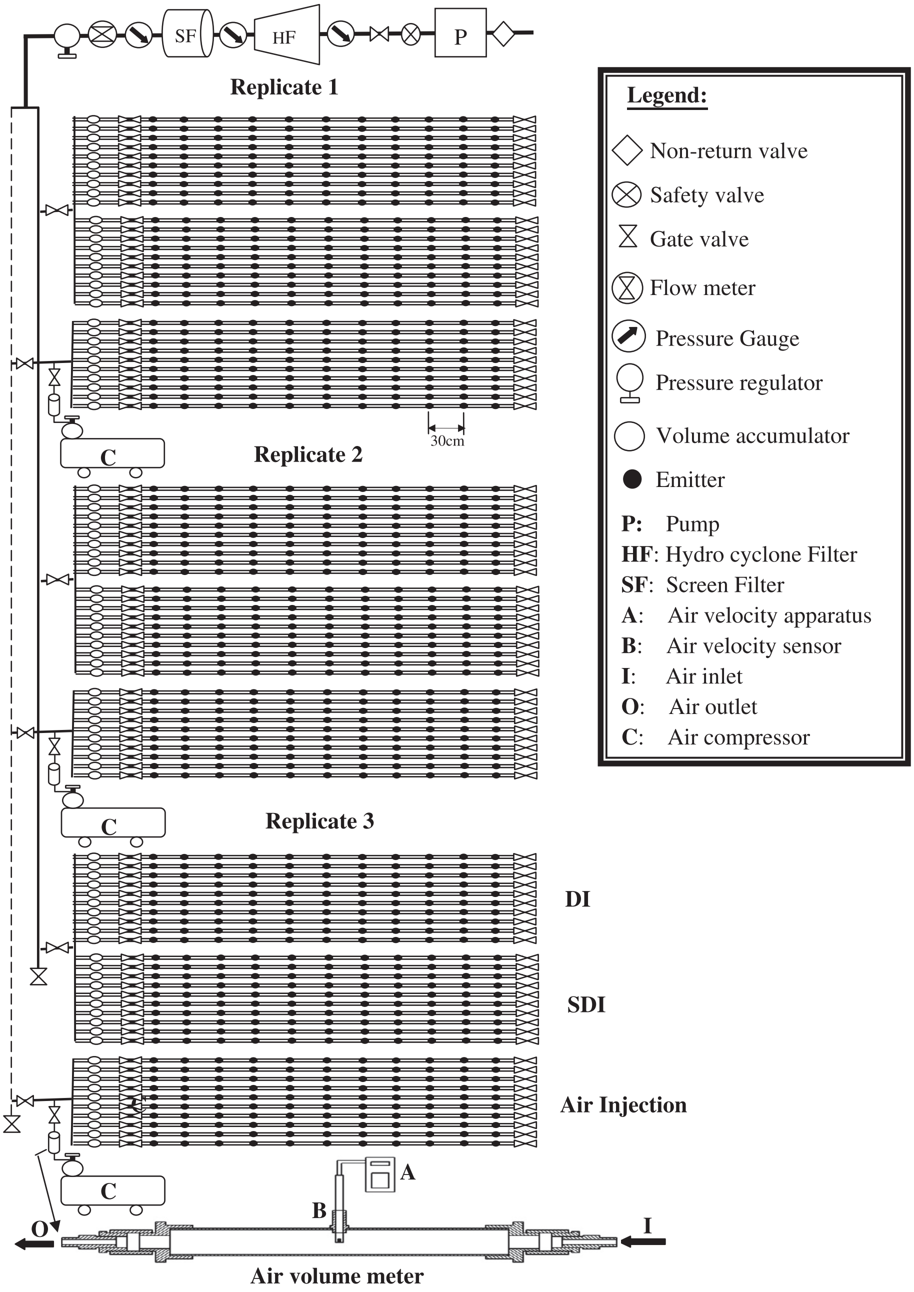

Fig. 1 Hydraulic diagram of the microirrigation system, air injection unit, and treatments.

discharge of the emitters in the sample and n is the number of emitters in the sample.

According to the recommended classification of manufacturer's coefficient of variation (CV) [14], the drippers were classified as excellent. The CV was 0.03 under 1 kPa operating pressure which represent the nominal pressure for the used emitters.

The second parameter of evaluation was the water distribution uniformity. It was conducted through the catch cans test immediately after installation of irrigation system by digging the soil around the emitter and putting a catch can under it and collecting the emitted water for 20 min, this operation was repeated monthly through the growing season to check the distribution uniformity. It was performed in three replicates to evaluate how evenly water was distributed. Twenty cans were used to perform this test and were distributed randomly in the area under study. Using a stopwatch, the water discharged from each dripper in a period of 15 min was caught inside the can and the volume of water caught was measured. The discharge in l/h for each dripper was calculated. The distribution uniformity of low quarter was calculated according to Burt et al. [15].

$$DU_{lq} = \frac{d_{lq}}{d_{ag}} \tag{3}$$

where DU_{lq} is the distribution uniformity low quarter, d_{lq} the lowest quarter depth (lowest 25% of the observed depths) and d_{avg} is the average depth of the total elements (cans). The average of the DU_{lq} for the three replicates was 95.61%.

Data recording

Weather data was recorded from an adjacent weather station. The center three rows of each plot were harvested, the grain yield per plot was calculated on a "wet-mass basis" (standard water content of 15.5%). Eight plants from each plot were also monitored and hand-harvested to determine growth and development parameters such as plant height, leaf area and stem diameter, and reproductive parameters such as days to flowering and grain filling duration. The data for leaf area, stem and root weight was derived from final plant harvest.

Water-use efficiency (WUE) and irrigation water-use efficiency (IWUE) values were calculated were calculated with Eqs. (4) and (5) [16]:

$$\mathrm{WUE} = \left(\frac{E_y}{E_t}\right) \times 100 \tag{4}$$

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

$$\mathrm{IWUE} = \left(\frac{E_y}{I_r}\right) \times 100 \tag{5}$$

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

Soil penetration resistance and plant take off force

Penetration resistance was measured by nine insertions in each plot before planting, and at every 2 weeks throughout the growing seasons. It was conducted using a handheld cone penetrometer (Eijkelkamp – Agrisearch Equipment, Netherlands). A penetrologger was used with 11.28 mm cone diameter, 30° angle and with vertical speeds that did not exceed 5 mm s^{-1} based on ASAE standard [17]. Penetrometer measurements were taken in X direction with 5 cm increments over the 0–50 cm depth, and at optimum soil moisture content (where the plowing can be performed).

The plant take off force (the force needed to remove plants from the soil) was measured at harvesting where the soil was dry, by taking 10 plants for each treatments and measurements were replicated three times in the experiment for each treatment. The take off force was conducted using a force gauge (Model M4-200, USA).

Statistical analysis

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, WUE, and IWUE as fixed effects for the irrigation treatment and growing seasons and the double interactions between them, and the replications as the error term [18].

Results and discussion

Plant populations for years 2010 and 2011 were approximately the same (55,556 plants ha^{-1}) because a planter was used and the rate of seeding was adjusted accurately. The crops were developed at a normal space each year. The first irrigation was made on 22 April of each year. The total irrigation water applied each year is shown in Table 3.

The WUE did not differ significantly between the two growing seasons but it differed significantly between treatments; the WUE was significantly greater for the air injection treatment compared with the DI and SDI (Table 3). The IWUE followed the same trend.

The cumulative water applied throughout the growing seasons was greater for DI for example at 12,970 m^3 ha^{-1} in 2010 compared to the SDI and air injection. The air injection had the lowest cumulative applied water in 2010 at 11,503 m^3 ha^{-1} (Table 3).

The air injection had the highest WUE and IWUE on both growing seasons, it was 1.442 kg m^{-3} and 1.096 kg m^{-3} in 2010 and 1.463 kg m^{-3} and 1.112 kg m^{-3} in 2011 for WUE and IWUE respectively in comparison with the DI treatment that had the lowest values of 0.928 kg m^{-3} and 0.937 kg m^{-3} in 2010 and 0.705 kg m^{-3} and 0.712 kg m^{-3} in 2011 for WUE and IWUE, respectively (Table 3).

The effect of treatments on grain weight per ear was significant. Aeration increased grain weight per ear and length compared to the DI and SDI on both growing season (Fig. 2).

The yield was significantly greater in both years for aeration compared to DI and SDI (Table 3). The yield of aerated treatment was higher than DI and SDI by 37.78% and 12.27% in 2010 and 38.46% and 12.5% in 2011.

The grains weight per ear were significantly heavier due to aeration compared to DI and SDI 79.8 g ear^{-1} versus 63.7 g ear^{-1} and 74.8 g ear^{-1} in 2010 for DI and SDI,

Table 3 Yield, seasonal irrigation, water use, water use efficiency and irrigation water use efficiency for corn under different treatments for two growing seasons.

Growing season	Treatments	Seasonal irrigation (m^3 ha^{-1})	Water use (m^3 ha^{-1})	Yield (kg ha^{-1})	WUE (kg m^{-3})	IWUE (kg m^{-3})
2010	DI	9857^a	12,970^a	9148^c	0.928^c	0.705^c
	SDI	9369^b	12,327^b	11,226^b	1.198^b	0.911^b
	Air injection	8742^c	11,503^c	12,605^a	1.442^a	1.096^a
2011	DI	9907^a	13,035^a	9286^c	0.937^c	0.712^c
	SDI	9416^b	12,389^b	11,428^b	1.214^b	0.922^b
	Air injection	8786^c	11,560^c	12,857^a	1.463^a	1.112^a

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

Fig. 2 The ear length for different treatments.

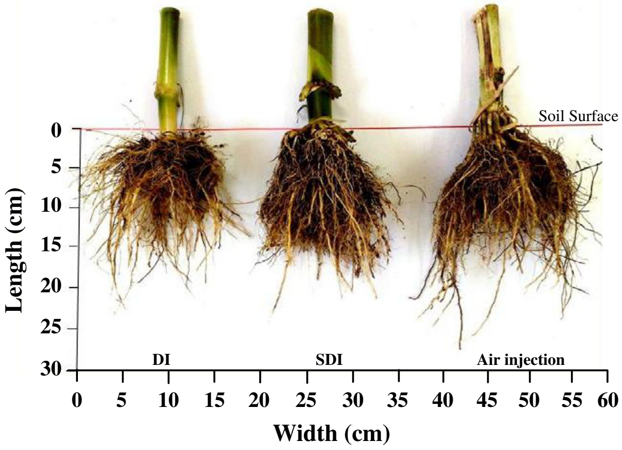

Fig. 3 The root shape under different treatments.

respectively, while it was 80 g ear^{-1} versus 65 g ear^{-1} and 75 g ear^{-1} in 2011 for DI and SDI, respectively (Table 4).

Plant height increased with aeration and plants were significantly taller than DI and SDI 284 cm versus 260 cm and 265 cm in 2010 for DI and SDI, respectively, while it was 290 cm versus 265 cm and 270 cm in 2011 for DI and SDI, respectively (Table 4).

A marked positive effect of aeration was observed on leaf area per plant where the air injection had the highest leaf area per plant with the lowest in DI treatment. Larger individual leaves was responsible 10,802 cm^2 versus 7312 cm^2 and 10,754 cm^2 in 2010 for DI and SDI, respectively, while it was 10,856 cm^2 versus 7349 cm^2 and 10,808 cm^2 in 2011 for DI and SDI, respectively (Table 4).

Stem diameter showed a positive response to aeration, there was a significant difference between air injection and both DI and SDI treatments. The air injection had the highest stem diameter followed by SDI and DI had the least values in both growing seasons (Table 4).

The number of leaves per plant showed significant differences between the aeration treatment and both SDI and DI treatments. The leaf area per plant was 1.477 and 1.0045 times greater in the aeration treatment than in DI and SDI respectively (Table 4).

The number of grains per plant was greater in the aerated treatment in comparison with DI and SDI (Table 4). With the air injection treatment, it was greater by 19.4% and 9.9% in 2010 and 20% and 10.2% in 2011 compared to DI and SDI, respectively.

The increase in 1000-grain weight by the air injection treatment over the DI treatment was 63.6% in 2010; and the increase in 2011 was 65.3%. The corresponding increase in 1000-grain weight for the air injection treatment over the SDI treatment was 7.4% in 2010; and in the 2011 was 8.3%. This result matched those obtained by other researchers in the Unites States and Australia [1–3,10,12], who observed increases in yields, improvements in growth characteristics and in soil quality related to root zone aeration.

Aeration had a slight effect on root length and width (Fig. 3); it increased the root dimensions in both horizontal and vertical axes related to when air was injected into the irrigation water. The aerated treatment had the greatest root length and width, followed by SDI, while the DI treatment had the smallest root dimensions (Fig. 3).

Cone index (soil penetration resistance) differed among DI, SDI and air injection treatments (Fig. 4). The maximum values of soil penetration resistance were 2.52 MPa, 2.00 MPa and 1.77 MPa for DI, SDI and air injection treatments respectively while the minimum values were 0.5 MPa, 0.17 MPa and 0.13 MPa respectively.

Because of the delicate nature of DI and SDI tapes, cultivation does not take place to depth, thereby predisposing the soil around the tapes to compaction. DI and SDI minimize alternate wetting and drying of the soil surface, a phenomenon that might otherwise predispose them to the cracking that could locally alleviate the lack of aeration that results in soil compaction and increases soil penetration resistance.

Table 4 Effect of DI, SDI and air injection on vegetative growth parameters of hybrid single 10-corn cultivar during 2010 and 2011.

Growing season	Treatments	Leaf area per plant (cm^2)	No. of leaves per plant	Stem diameter (mm)	Plant height (cm)	No. of grains per plant	Grains weight per ear (kg)	1000-Grain weight (g)
2010	DI	7312^c	9^c	22.4^b	260^b	532^c	0.0637^b	89.87^c
	SDI	10,754^b	12^b	23.9^b	265^b	578^b	0.0748^{ab}	136.87^b
	Air injection	10,802^a	14^a	26.9^a	284^a	635^a	0.0798^a	147.06^a
2011	DI	7349^c	11^c	22.5^c	265^c	540^c	0.0650^b	91.10^c
	SDI	10,808^b	14^b	24.0^b	270^b	588^b	0.0750^{ab}	139.10^b
	Air injection	10,856^a	15^a	27.0^a	290^a	648^a	0.0800^a	150.60^a

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

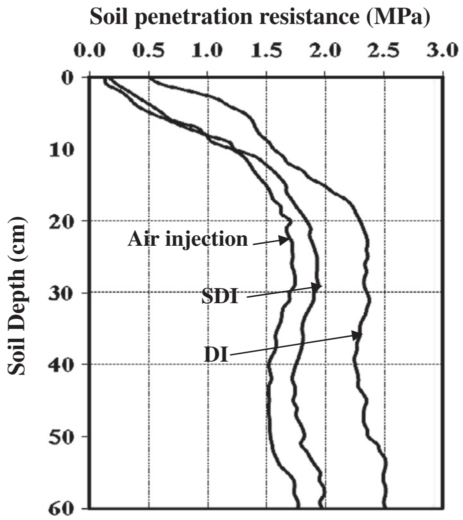

Fig. 4 Relationship between penetration resistance and different irrigation treatment at the optimum soil moisture content.

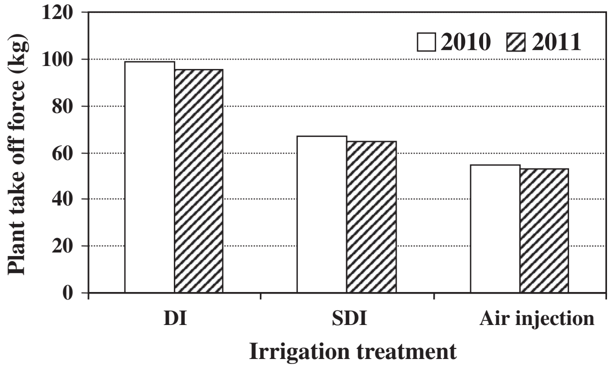

Fig. 5 The plants take off force under different treatments at harvest.

With regard to the plant take off force (Fig. 5), the maximum value 98.7 kg was obtained under DI and the lowest value was 53.2 kg under air injection. The plant take off force decreased with air injection by about 80% and 22% comparing with DI and SDI, respectively. This suggests that under air injection the cohesion force between the root and soil is low, and that the adhesion force between the soil particles is low, so the take off force for plant is reduced with air injection.

Conclusion

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 corn productivity.

The available indigenous materials can be used for aeration in different soil types and conditions in order to increase the returns on corn production. The cultivation technique developed in this study can be applied to other vegetable and field crops as well as corn and can be utilized even in wet lowlands otherwise considered as wastelands.

In addition to yield, growth characteristics, plant take off force and soil penetration resistance, future studies should focus on the impact of air injection on soil respiration, soil salinity, soil microbial activity and insect/pest resistance.

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